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European Patent Office
Office européen des brevets

(19)

(11) Publication number: **0 379 374 B1**

EUROPEAN PATENT SPECIFICATION

(12)

(45) Date of publication of patent specification: **20.07.94**

(51) Int. Cl.5: **G01R 33/022**, G01R 33/025

(21) Application number: **90300540.3**

(22) Date of filing: **18.01.90**

(54) **Measuring magnetic fields.**

(30) Priority: **20.01.89 JP 12890/89**
14.02.89 JP 32824/89

(43) Date of publication of application:
25.07.90 Bulletin 90/30

(45) Publication of the grant of the patent:
20.07.94 Bulletin 94/29

(84) Designated Contracting States:
DE FR GB

(56) References cited:
EP-A- 0 156 086
CA-A- 1 129 961
FR-A- 1 523 462
US-A- 3 956 690

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EP 0 379 374 B1

Description

The present invention relates to the measurement of magnetic fields, for example to an apparatus for eliminating, in measuring a very weak magnetic field, external magnetic noise components generated by other magnetic sources and mixed in with the very weak magnetic field to be measured.

In recent years, a very weak magnetic field produced by a human body, etc., is measured by a highly sensitive apparatus employing a SQUID (superconducting quantum interference device).

In measuring the very weak magnetic field, external magnetic noise causes a problem. Sources of the external magnetic noise are geomagnetism, electric cars, elevators, electric appliances such as computers, etc. These sources are located very far, compared to a distance between a pickup coil of the measuring apparatus and a source of the very weak magnetic field to be measured. The external magnetic noise may therefore be considered as a uniform magnetic field or uniform gradient field whose direction do not change around the source of the very weak magnetic field.

Based on this assumption, the external magnetic noise can be removed by employing, as the pickup coil, a garadiometer such as a first-order gradiometer and a second-order gradiometer. This type of pickup coil has, however, manufacturing errors which prevent a complete removal of the noise.

It is desirable to provide an apparatus for measuring a magnetic field, which surely removes noise caused by a uniform magnetic field as well as remaining noise caused by an imbalance in the gradiometer.

CA-A-1 129 961 discloses a magnetic field measuring apparatus according to the preamble of accompanying claim 1. In this apparatus the compensation coils are supposed to be orthogonal to one another. In practice, as will be described below, manufacturing errors are inevitably present that prevent a satisfactory elimination of noise. Therefore, this apparatus is unsatisfactory.

JP-A-60-58565 discloses a similar magnetic field measuring apparatus using an orthogonal triple-axis magnetometer as the compensation coils.

According to the present invention there is provided an apparatus for measuring a very weak magnetic field generated by for example a human body, comprising:-

a gradiometer;

a magnetic field measuring circuit for measuring a magnetic field from an output signal of said gradiometer;

at least three compensation coils for detecting a uniform magnetic field or a uniform gradient magnetic field existing around said gradiometer, said three compensation coils being oriented in three different directions that are not all in the same plane;

at least three magnetic field measuring circuits for measuring magnetic fields in respective ones of said directions according to output signals of said compensation coils; and

a magnetic noise eliminating circuit for eliminating magnetic noise from the output signal of said gradiometer by using the output signals of said three magnetic field measuring circuits;

characterised in that:-

sensitivity values of said three magnetic field measuring circuits are individually set in advance by applying, to said compensation coils and said gradiometer, uniform magnetic fields in three different directions that are not all in the same plane and by solving equations of the following form:

$$b_1V_{1x} + b_2V_{2x} + b_3V_{3x} = V_{0x}$$
$$b_1V_{1y} + b_2V_{2y} + b_3V_{3y} = V_{0y}$$
$$b_1V_{1z} + b_2V_{2z} + b_3V_{3z} = V_{0z}$$

where x, y, z represent said three different directions b_1, b_2 and b_3 represent said sensitivity values of the magnetic field measuring circuits, V_1, V_2 and V_3 represent the output signals of said compensation coils and V_0 represents the output signal of said gradiometer;

whereby a mutually-orthogonal orientation of said compensation coils is not necessary.

According to the present invention, the gradiometer detects the magnetic field of an object to be measured as well as magnetic noise from an external uniform magnetic field. Three compensation coils oriented substantially in different directions detect the magnetic noise in those directions. Magnetic noise components detected by the three compensation coils are weighted and added to each other to find a noise magnetic field existing around the gradiometer. The noise is subtracted from an output of the gradiometer to obtain a correct magnetic field of the object to be measured. In this way, a very weak magnetic field in a human body can be correctly measured.

Reference will now be made by way of example to the accompanying drawings, wherein:-

Fig. 1A is a schematic view showing a previously-considered apparatus for measuring a magnetic field with the use of a first-order gradiometer;

Fig. 1B is a schematic view showing an apparatus for measuring a magnetic field employing a second-order gradiometer according to the prior art;

Fig. 2A is a perspective view showing a method of removing noise with the use of a first-order gradiometer and superconducting tabs according to the prior art;

Fig. 2B is a perspective view showing a method of removing noise of a first-order gradiometer by superconducting tabs and compensation loops according to the prior art;

Fig. 3 is a schematic view showing an apparatus for measuring a magnetic field employing three compensation coils according to a prior art;

Fig. 4 is a block diagram showing an apparatus for measuring a magnetic field according to a first aspect of the present invention;

Fig. 5 is a circuit diagram showing the details of the respective parts of the apparatus of Fig. 4;

Fig. 6A is a perspective view showing an arrangement of a second-order gradiometer and compensation coils of the apparatus of Figs. 4 and 5;

Fig. 6B is a perspective view showing a way of winding the pickup coil of Fig. 6A;

Fig. 6C is a perspective view showing a way of winding each compensation coil of Fig. 6A;

Fig. 7 is a perspective view showing another arrangement of the second-order gradiometer and compensation coils of the apparatus of Figs. 4 and 5;

Fig. 8 is a circuit diagram showing the details of a magnetic noise eliminating circuit of Fig. 5;

Fig. 9 is a circuit diagram showing a magnetic noise eliminating circuit similar to that of Fig. 5 but realized by a digital circuit:

Fig. 10 is a circuit diagram showing a magnetic noise eliminating circuit similar to that of Fig. 5 but realized by a digital circuit and a computer;

Fig. 11 is a perspective view showing a uniform magnetic field generator of Fig. 10;

Figs. 12 and 13 are flowcharts showing control examples of the digital circuit with the computer of Fig. 10;

Fig. 14 is a block diagram showing an apparatus for measuring a magnetic field according to a second aspect of the invention;

Fig. 15 is a circuit diagram showing the details of a magnetic noise eliminating circuit of Fig. 14;

Fig. 16 is a circuit diagram showing a modification of the magnetic noise eliminating circuit of Fig. 14;

Fig. 17 is a block diagram showing an apparatus for measuring a magnetic field according to the first aspect of the invention, with three gradiometers compensated by one set of compensation coils;

Fig. 18 is a perspective view showing the details of the compensation coils and second-order gradiometers of Fig. 17; and

Fig. 19 is a block diagram showing an apparatus for measuring a magnetic field according to the second aspect of the invention, with three gradiometers compensated by one set of compensation coils.

Before describing the preferred embodiments, an explanation will be given of various forms of apparatus for measuring a magnetic field shown in Figs. 1A to 3.

To remove magnetic noise caused by an external uniform magnetic field, a derivative magnetic field detection coil (hereinafter referred to as the gradiometer) such as a first-order gradiometer 10 shown in Fig. 1A may be employed. To remove a uniform gradient magnetic field, a second-order gradiometer 100 shown in Fig. 1B may be employed. In addition to these pickup coils, various types of derivative pickup coils such as third-order gradiometer (not shown) may be employed.

The pickup coil 10 and an input coil 41b are made of superconducting material to form a superconducting loop, and the input coil 41b is magnetically connected to a highly sensitive magnetic sensor SQUID (super conducting quantum interference device) 41a. When a magnetic field H is applied to the pickup coil 10, a current I flows through the pickup coil 10 and input coil 41b. The current I is proportional to magnetic flux ϕ_p intersecting the pickup coil 10, and the current I is oriented to cancel the magnetic flux ϕ_p. Magnetic flux Oi from the input coil 41b intersects the SQUID 41a and is detected by the SQUID 41a. An output of the SQUID 41a is processed by a magnetic field measuring circuit 41c, which outputs a signal Vo corresponding to the intersecting magnetic flux. The signal Vo is converted by a voltage-current converting circuit 41d into a current proportional to the signal Vo. The current flows to a feedback coil 41e magnetically connected with the SQUID 41a, such that magnetic flux is fed back to the SQUID 41a to cancel the magnetic flux ϕ_i input into the SQUID 41a from the input coil 41b. Using a null method, the magnetic flux ϕ_i, i.e., the magnetic field H is measured, and an output end of the magnetic field measuring circuit 41c provides a signal proportional to the magnetic field H.

The portion surrounded by a dotted line in Figs. 1A and 1B is a magnetic field measuring device 41.

For the sake of simplicity, a first-order gradiometer will be adopted to explain an equivalent coil of the gradiometer coil with respect to a uniform magnetic field.

As shown in Fig. 1A, the first-order gradiometer comprises two component coils. Supposing the areas of the coils and the unit vectors normal to coil planes are A_1, $\mathbf{n}_1$ and A_2, $\mathbf{n}_2$, the magnetic flux ϕ of a uniform magnetic field H intersecting the gradiometer is expressed as follows:

$$\phi = (A_{1n1} \bullet \mathbf{H}) + (A_{2n2} \bullet \mathbf{H}) \qquad (1)$$

where the value between each pair of parentheses is a scalar product.

The scalar product is obtainable by multiplying a product of absolute values of two vectors by a cosine of an angle formed by the two vectors. This may be represented by a sum of products of three components on respective rectangular coordinate axes of the two vectors.

Conditions to zero the magnetic flux ϕ are as follows:

$$A_{1n1} = -A_{2n2} \qquad (2)$$

Namely, the areas of the two coil planes shall be equal to each other, and the normal directions of the coil planes shall be correctly opposite to each other. The coils involve, however, manufacturing errors, and therefore, the equation (2) is not actually satisfied. Accordingly, the gradiometer provides an output due to the uniform magnetic field.

Supposing

$$A_2 + A_1 + \Delta A$$
$$n_2 = -(\mathbf{n}_1 + \Delta_n),$$

then the intersecting magnetic flux ϕ is expressed as follows;

$$\begin{aligned} \phi &= (A_1 \mathbf{n}_1 \cdot \mathbf{H}) - ([A_1 + \Delta A][\mathbf{n}_1 + \boldsymbol{\Delta}_n] \cdot \mathbf{H}) \\ &= (-[A_1 \boldsymbol{\Delta}_n + \Delta A[\mathbf{n}_1 + \boldsymbol{\Delta}_n] \cdot \mathbf{H}) \qquad \cdots (3) \end{aligned}$$

In this equation (3), the bold type part indicates a vector quantity. Supposing the size of the vector is Ae and its normal direction is ne, the equation (3) is expressed as follows:

$$\phi = (A_{ene} \bullet \mathbf{H}) \qquad (4)$$

This is equal to magnetic flux produced by a coil intersecting the uniform magnetic field and having an area of Ae and a normal direction of $\mathbf{n}_e$. Namely, if the two component coils forming the gradiometer do not satisfy the equation (2) with respect to the uniform magnetic field, the gradiometer will be an equivalent of the coil having the area A_e and normal direction $\mathbf{n}_e$. In this case, the gradiometer is sensitive to the uniform magnetic field.

For any other gradiometer, it is said that the coil will be an equivalent of a coil having a certain area and a certain direction, if the coil has manufacturing errors.

Generally, a manufactured coil has an area A involving an error ratio of about 0.1% or more. In addition, the parallelism of component coils of the manufactured coil involve errors. Therefore, the coil can reduce external magnetic noise only to about a thousandth.

To deal with this problem, Fig. 2A shows an arrangement of three superconducting tabs 12X, 12Y, and 12Z each being a thin plate having a small area (U.S. Pat. No.3,976,938). The tabs are arranged to change a sensitivity in one of three orthogonal axes of a magnetic field. Positions of the tabs are adjusted in the directions of arrow marks X, Y, and Z shown in Fig. 2A to change a distribution of the magnetic field. Alternatively, as shown in Fig. 2B, three compensation loops 13X, 13Y, and 13Z are arranged orthogonally to each other (U.S. Pat. Nos.3,956,690, 3,965,411). Superconducting tabs 12X, 12Y, and 12Z are moved to adjust the magnetism blocking quantities of the superconducting tabs with respect to the compensation loops. In both cases, an imbalance of the pickup coil 10 due to manufacturing errors is compensated through the adjustment of the tabs.

The above adjusting operations are, however, quite troublesome because an external uniform AC magnetic field must be applied along each normal of the planes of the superconducting tabs 12x, 12Y, and

12Z and compensation loops 13X, 13Y, and 13Z to minimize an output of the magnetic field measuring device. In addition, the normals of the planes of the three superconducting tabs 12X, 12Y, and 12Z and three compensation loops 13X, 13Y, and 13Z shall correctly be orthogonal to each other. They actually involve, however, manufacturing errors so that, if the device is adjusted in a certain axial direction to provide no output with respect to the uniform magnetic field, an output of the device for another axial direction with respect to the uniform magnetic field may be increased. Repetitive adjusting operations may minimize a noise output due to the uniform magnetic field but it cannot completely cancel the noise.

Figure 3 shows another technique employing three compensation coils 11, 12, and 13. Normals of the planes of the coils are oriented in directions X, Y, and Z to remove noise caused by a uniform magnetic field. This technique is disclosed in Japanese Unexamined Patent Publication (Kokai) No. 63-32384. In Fig. 3, numeral 91 denotes a coil for detecting a magnetic field; 92 an input coil 93 a SQUID, 94 a feedback coil, 95 a current source, 96 an output voltage detecting circuit, 97 a variable gain amplifier, and R a feedback resistor.

According to this technique, the magnetic noise is cancelled for each of the directions X, Y, and Z. Therefore, to carry out the adjustment correctly in a short time, the normals of the planes of the three compensation coils must correctly be orthogonal to each other, and the externally applied uniform magnetic field must be exactly aligned with each normal to adjust variable resistors. Since errors tend to occur in the directions of the coil planes as well as in the direction of the uniform magnetic field, even repetitive adjustments cannot completely eliminate the noise caused by the uniform magnetic field.

According to the former technique, a uniform AC magnetic field is externally applied, and the superconducting tabs and compensation loops are successively adjusted to minimize an output of the magnetic field measuring device. This adjustment is troublesome. According to the latter technique, the normals of the planes of the three superconducting tabs and three compensation loops shall correctly be orthogonal to each other. They inevitably involve, however, manufacturing errors that prevent a satisfactory elimination of the noise caused by the uniform magnetic field.

Figure 4 is a block diagram showing an embodiment according to the first aspect of the present invention. In the figure, numerals 11, 12, and 13 denote compensation coils. The planes of the coils are set such that the magnetic flux of a uniform magnetic field of optional direction intersects at least one of the coils. Numeral 10 denotes a gradiometer. Numerals 21, 22, 23, and 20 denote magnetic field measuring circuits for outputting signals proportional to magnetic flux intersecting the compensation coils 11 to 13 and pickup coil 10, respectively. Numerals 401, 402, and 403 denote multiplication circuits for amplifying the outputs of the magnetic field measuring circuits 21, 22, and 23, respectively. The multiplication circuits 401 to 403 receive weights for changing multiplication factors. Numeral 5 denotes an addition and subtraction circuit for subtracting outputs of the multiplication circuits 401 to 403 from an output of the magnetic field measuring circuit 20. The multiplication circuits 401 to 403 and the addition and subtraction circuit 5 form a magnetic noise eliminating circuit 30.

Figure 5 shows the details of the apparatus of Fig. 4 of the invention. Each of the magnetic field measuring circuits 21, 22, 23, and 20 comprises an input coil 41b, a SQUID 41a, a feedback coil 41e, a magnetic field measuring circuit 41c and a voltage-current converting circuit 41d. The functions of these elements are the same as those of the corresponding circuits shown in Fig. 1A. The multiplication circuits 401 to 403 of the magnetic noise eliminating circuit 30 actually comprise variable gain amplifiers 411 to 413 respectively, and the addition and subtraction circuit 5 actually comprises a differential amplifier 50.

Operation of the apparatus of Fig. 5 will be explained next. A uniform magnetic field is successively applied along axes X, Y, and Z. When the uniform magnetic field is applied along the axis X, the magnetic field measuring circuits 21, 22, 23, and 20 provide outputs V_{1X}, V_{2X}, V_{3X} and V_{0X}, respectively. When the uniform magnetic field is applied along the axis Y, the magnetic field measuring circuits 21, 22, 23, and 20 provide outputs V_{1Y}, V_{2Y}, V_{3Y}, and V_{0Y} respectively. When the uniform magnetic field is applied along the axis Z, the magnetic field measuring circuits 21, 22, 23, and 20 provide outputs V_{1Z}, V_{2Z}, V_{3Z}, and V_{0Z}, respectively. If the gains of the variable gain amplifiers 411 to 413 are adjusted so that the outputs of the variable gain amplifiers satisfy the following equations (5), the output of the differential amplifier 50 provides a signal from which the noise caused by the uniform magnetic field has been removed:

$$\begin{aligned} b_1V_{1X} + b_2V_{2X} + b_3V_{3X} &= V_{0X} \\ b_1V_{1Y} + b_2V_{2Y} + b_3V_{3Y} &= V_{0Y} \\ b_1V_{1Z} + b_2V_{2Z} + b_3V_{3Z} &= V_{0Z} \qquad (5) \end{aligned}$$

where b_1, b_2, and b_3 are the gains of the variable gain amplifiers 411 to 413, respectively. The gains may be positive and negative values.

It is supposed that the magnitude of intersecting magnetic flux derived from the uniform magnetic field becomes maximum when the direction of the uniform magnetic field is normal to the plane of a coil, and that unit vectors normal to the planes of the coils 11 to 13 and 10 are defined as n_1, n_2, n_3, and n_0, respectively. When the uniform magnetic field having a vector H is applied in an optional direction, outputs of the variable gain amplifiers 411 to 413 and magnetic field measuring circuit 20 will be $b_1a_1(\mathbf{n}_1 \cdot \mathbf{H})$, $b_2a_2(\mathbf{n}_2 \cdot \mathbf{H})$, $b_3a_3(\mathbf{n}_3 \cdot \mathbf{H})$ and $a_0(\mathbf{n}_0 \cdot \mathbf{H})$, respectively. Here, a_1 is a constant determined by an area of the coil 11 and the characteristics of the magnetic field measuring circuit 21; a_2 a constant determined by an area of the coil 12 and the characteristics of the magnetic field measuring circuit 22; and a_3 a constant determined by an area of the coil 13 and a gain of the magnetic field measuring circuit 23. The constant a_0 is determined by an effective area of the gradiometer 10 when the intersecting magnetic flux derived from the uniform magnetic field becomes maximum and by a gain of the magnetic field measuring circuit 20 (a_0 will be zero if the gradiometer 10 has no manufacturing error). The value between each pair of parentheses is a scalar product.

Supposing the three orthogonal axis components of the vector **H** are H_X, H_Y, and H_Z and axial unit vectors **i**, **j**, and **k** the above outputs will be expressed as follows:

$$
\begin{aligned}
&b_1a_1(\mathbf{n}_1 \cdot \mathbf{H}) = b_1a_1[(\mathbf{n}_1 \cdot \mathbf{i}H_X) + (\mathbf{n}_1 \cdot \mathbf{j}H_Y) + (\mathbf{n}_1 \cdot \mathbf{k}H_Z)]\\
&b_2a_2(\mathbf{n}_2 \cdot \mathbf{H}) = b_2a_2[(\mathbf{n}_2 \cdot \mathbf{i}H_X) + (\mathbf{n}_2 \cdot \mathbf{j}H_Y) + (\mathbf{n}_2 \cdot \mathbf{k}H_Z)]\\
&b_3a_3(\mathbf{n}_3 \cdot \mathbf{H}) = b_3a_3[(\mathbf{n}_3 \cdot \mathbf{i}H_X) + (\mathbf{n}_3 \cdot \mathbf{j}H_Y) + (\mathbf{n}_3 \cdot \mathbf{k}H_Z)]\\
&a_0(\mathbf{n}_0 \cdot \mathbf{H}) = a_0[(\mathbf{n}_0 \cdot \mathbf{i}H_X) + (\mathbf{n}_0 \cdot \mathbf{j}H_Y) + (\mathbf{n}_0 \cdot \mathbf{k}H_Z)] \qquad (6)
\end{aligned}
$$

To obtain a sum of the outputs of the variable gain amplifiers 411 to 413 equal to an output of the magnetic field measuring circuit 20 irrespective of the direction and magnitude of the uniform magnetic field, the following must be satisfied irrespective of the vector **H**:

$$b_1a_1(\mathbf{n}_1 \cdot \mathbf{H}) + b_2a_2(\mathbf{n}_2 \cdot \mathbf{H}) + b_3a_3(\mathbf{n}_3 \cdot \mathbf{H}) = a_0(\mathbf{n}_0 \cdot \mathbf{H}) \qquad (7)$$

This is expressed as follows:

$$
\begin{aligned}
&(b_1a_1n_{1X} + b_2a_2n_{2X} + b_3a_3n_{3X})H_X\\
&+ (b_1a_1n_{1Y} + b_2a_2n_{2Y} + b_3a_3n_{3Y})H_Y\\
&+ (b_1a_1n_{1Z} + b_2a_2n_{2Z} + b_3a_3n_{3Z})H_Z\\
&= a_0n_{0X}H_X + a_0n_{0Y}H_Y + a_0n_{0Z}H_Z \qquad (8)
\end{aligned}
$$

To satisfy the equation (8) irrespective of the values H_X, H_Y, and H_Z, coefficients of the values H_X, H_Y, and H_Z must be equal to each other on both sides. Namely, the following must be satisfied:

$$
\begin{aligned}
&(b_1a_1n_{1X} + b_2a_2n_{2X} + b_3a_3n_{3X})H_X = a_0n_{0X}H_X\\
&(b_1a_1n_{1Y} + b_2a_2n_{2Y} + b_3a_3n_{3Y})H_Y = a_0n_{0Y}H_Y\\
&(b_1a_1n_{1Z} + b_2a_2n_{2Z} + b_3a_3n_{3Z})H_Z = a_0n_{0Z}H_Z \qquad (9)
\end{aligned}
$$

Respective terms of the equations (9) and the above-mentioned actually measured values have the following relations:

$$
\begin{aligned}
&a_1n_{1X}H_X = V_{1X},\ a_2n_{2X}H_X = V_{2X},\ a_3n_{3X}H_X = V_{3X},\ a_0n_{0X}H_X = V_{0X},\\
&a_1n_{1Y}H_Y = V_{1Y},\ a_2n_{2Y}H_Y = V_{2Y},\ a_3n_{3Y}H_Y = V_{3Y},\ a_0n_{0Y}H_Y = V_{0Y},\\
&a_1n_{1Z}H_Z = V_{1Z},\ a_2n_{2Z}H_Z = V_{2Z},\ a_3n_{3Z}H_Z = V_{3Z},\ a_0n_{0Z}H_Z = V_{0Z}, \qquad (10)
\end{aligned}
$$

Therefore, the equations (9) will be written as follows:

$$
\begin{aligned}
&b_1V_{1X} + b_2V_{2X} + b_3V_{3X} = V_{0X}\\
&b_1V_{1Y} + b_2V_{2Y} + b_3V_{3Y} = V_{0Y}\\
&b_1V_{1Z} + b_2V_{2Z} + b_3V_{3Z} = V_{0Z} \qquad (11)
\end{aligned}
$$

From the simultaneous equations (11), three unknown values b_1, b_2 and b_3 are found, and the gains of the variable gain amplifiers 411, 412, and 413 are set to the values b_1, b_2, and b_3, respectively. As a result, with respect to the uniform magnetic field of optional direction, a sum of the outputs of the left sides, i.e., a sum of the outputs of the variable gain amplifiers 411 to 413, may be made equal to an output of the magnetic

field measuring circuit 20. As a result, the noise due to the uniform magnetic field is removed from the output of the differential amplifier 50.

The compensation coils 11 to 13 are located farther than the coil 10 from a magnetic source to be measured, so that a magnetic field Hs to be measured reaches the coils 11 to 13 in very small quantity compared to a quantity thereof reaching the coil 10. Therefore, even if the outputs of the magnetic field measuring circuits are subtracted from the output of the magnetic field measuring circuit 20, an output component of the magnetic field measuring circuit 20 derived from the magnetic field Hs to be measured will remain substantially as it is and will be transferred to the differential amplifier 50.

In the above explanation, for the sake of simplicity, a uniform magnetic field is successively applied along three orthogonal axes to find the values b_1, b_2, and b_3. It is not necessary, however, to apply the uniform magnetic field along the three orthogonal axes. The uniform magnetic field may be applied in any three different directions that are not all in the same plane. It is supposed that magnetic fields $\mathbf{H}_1$, $\mathbf{H}_2$, and $\mathbf{H}_3$ of three directions satisfying the above conditions are successively applied. When the uniform magnetic field $\mathbf{H}_1$ is applied, the magnetic field measuring circuits 21 to 23 and 20 provide outputs V_{1X}, V_{2X}, V_{3X}, and V_{0X}, respectively. When the uniform magnetic field $\mathbf{H}_2$ is applied, the magnetic field measuring circuits 21 to 23 and 20 provide outputs V_{1Y}, V_{2Y}, V_{3Y}, and V_{0Y}, respectively. When the uniform magnetic field $\mathbf{H}_3$ is applied, the magnetic field measuring circuits 21 to 23 and 20 provide outputs V_{1Z}, V_{2Z}, V_{3Z}, and V_{0Z}, respectively. Thereafter, the gains of the variable gain amplifiers are adjusted so that the outputs of the variable gain amplifiers satisfy the equations (11). As a result, the output of the differential amplifier 50 provides a signal from which the noise caused by the uniform magnetic field has been removed.

Figure 6A shows a probe 60 for holding the compensation coils 11 to 13 and pickup coil 10 shown in Figs. 4 and 5. The probe 60 comprises a SQUID chip holder 61 for accommodating the magnetic field measuring circuits 20 to 23, a pickup coil supporting material 62 for holding the second-order gradiometer 10, and a compensation coil supporting material 63 for supporting the compensation coils 11 to 13. Around the pickup coil supporting material 62, the pickup coil 10 is wound in a manner as shown in Fig. 6B. At the top of the compensation coil supporting material 63, compensation coil chips 64 are disposed on faces X, Y, and Z, respectively. The compensation coil chips 64 hold the compensation coils 11 to 13. Each of the compensation coils 11 to 13 is a single winding coil as shown in Fig. 6C. The compensation coil supporting material 63 is received in an opening 65 formed on the pickup coil supporting material 62. Numeral 66 denotes a hole for receiving a rod that protrudes from the bottom of the compensation coil supporting material 63.

The compensation coil chips 64 supported by the compensation coil supporting material 63 comprise wafers on which the compensation coils 11 to 13 are formed. The compensation coil chips 64 are fixed to the three faces X, Y, and Z of a cube. The compensation coil supporting material 63 with the fixed coil chips 64 is assembled and embedded in an open block 65 of the pickup coil supporting material 62 to make a SQUID sensor, which is resistant to strain from vibration and aging and demonstrates a high S/N ratio. Signals picked up by the pickup coil 10 and compensation coils 11 to 13 are applied to the magnetic field measuring circuits 20 to 23 disposed inside the SQUID chip holder 61 at the upper part of the probe 60. The signals are then converted by the circuits 20 to 23 into signals or pulses proportional to the strength of the magnetic field, and output outside.

Figure 7 shows another embodiment of the probe 60 for holding the compensation coils 11 to 13 and pickup coil 10. In the figure, numeral 67 denotes a pickup coil bobbin, and 68 a compensation coil holder. This embodiment is characterized in that the pickup coils 10 is formed by lithography etching.

Figure 8 shows the details of the differential amplifier 50 of the magnetic noise eliminating circuit 30 of Fig. 5. In Fig. 8, the magnetic field measuring circuits 20 to 23 and variable gain amplifiers 411 to 413 are the same as those shown in Fig. 5, and therefore, their explanations will be omitted. The differential amplifier 50 comprises an addition circuit 51 having resistors R_1 to R_4 and an operational amplifier 51a; an addition circuit 52 having resistors R_5 to R_7 and an operational amplifier 52a; and an inverting amplifier 53 having resistors R_8 and R_9 and an operational amplifier 53a. In the differential amplifier 50, the addition circuit 55 adds outputs of the variable gain amplifiers 411 to 413 to each other, and the addition result is inverted and output to the addition circuit 52. In the addition circuit 52, the inverted addition result is added to the output of the magnetic field measuring circuit 20. Namely, the outputs of the variable gain amplifiers 411 to 413 are subtracted from the output of the magnetic field measuring circuit 20. The subtracted result is inverted and output to the inverting amplifier 53. The inverting amplifier 53 again inverts the subtracted result inverted by the addition circuit 52 to return the same to a normal value. As a result, a signal from which the noise caused by a uniform magnetic field and caused by far external noise sources has been removed is obtainable.

Figure 9 shows a digital circuit achieving a function of the magnetic noise eliminating circuit 30 of Fig. 5. In this embodiment, the magnetic noise eliminating circuit 30 comprises multiplication circuits 421, 422, and 423, an addition and subtraction circuit 54, and a timing pulse generator 6. The multiplication circuits 421, 422, and 423 comprise sample-hold circuits 421a, 422a, and 423a for helping the normal operation of analog-to-digital converters by sampling and holding analog signal values at an optional time, analog-to-digital converters (hereinafter referred to as A/D converters) 421b, 422b, and 423b, multipliers 421c, 422c, and 423c, and registers 421d, 422d, and 423d.

The addition and subtraction circuit 54 comprises a sample-hold circuit 54a, and A/D converter 54b, and an adder 54c.

In this arrangement, outputs of the magnetic field measuring circuits 20 to 23 are sampled at certain intervals based on signals from the timing pulse generator 6. The sampled outputs are converted into digital signals by the A/D converters 421b, 422b, 423b, and 54b, respectively. In the same manner as the previous embodiment, the values b_1, b_2 and b_3 are found.

These values are set in the registers 421d, 422d, and 423d, respectively. When an objective magnetic field is measured, detected values are multiplied by the values b_1, b_2, and b_3 in the A/D converters 421b, 422b, and 423b, respectively, and then the values are subtracted from the output of the A/D converter 54b in the adder 54c. As a result, a digital signal from which the noise of the uniform magnetic field has been removed is obtainable. Since an output of the addition and subtraction circuit 54 is a digital value, the output is converted into an analog value by the D/A converter 55 and output from the magnetic noise eliminating circuit 30.

Figure 10 shows another embodiment in which a digital circuit realizes a function of the magnetic noise eliminating circuit 30 of Fig. 5. The same parts as those shown in Fig. 9 are represented by like reference numerals. The difference between the embodiment of Fig. 10 from that of Fig. 9 will be explained next. The noise removing circuit 30 of Fig. 9 processes signals from the magnetic field measuring circuits 20 to 23 by hardware, while the embodiment of Fig. 10 converts signals from the magnetic field measuring circuits 20 to 23 into digital signals and processes the digital signals by software with the use of a processor (a computer) 31. Similar to the embodiment of Fig. 9, an output of the processor 31 is a digital signal, which is therefore converted into an analog signal and output from the magnetic noise eliminating circuit 30. The embodiment of Fig. 10 employs a uniform magnetic field generator 8 connected to a timing pulse generator 6 through a sine wave generator 7.

Figure 11 shows an arrangement of the uniform magnetic field generator 8 comprising a cylindrically wound coil. A uniform magnetic field H to be generated is in parallel with an axis of the cylindrical coil. The compensation coils 11 to 13 and pickup coil 10 explained in the previous embodiment are disposed in the center of the cylindrical coil. By changing the axial directions of the respective coils, a uniform AC magnetic field is successively applied along the three orthogonal axes X, Y, and Z, and the maximum values V_{1X}, V_{1Y}, V_{1Z}, V_{2X}, V_{2Y}, V_{2Z}, V_{3X}, V_{3Y}, V_{3Z}, V_{0X}, V_{0Y}, and V_{0Z} of AC outputs of the magnetic field measuring circuits 20 to 23 are measured in the respective directions. Based on the equation (11), the gain values b_1, b_2, and b_3 are calculated, and the values are set in the variable gain amplifiers 411 to 413, thereby providing a signal from which the noise due to the uniform magnetic field has been removed.

Figs. 12 and 13 are flowcharts showing the operation of the processor 31 of Fig. 10. Figure 12 shows weighting operation sequences. In Step 121, an initialization is carried out. In Step 122, the uniform magnetic field generator 8 applies a uniform magnetic field successively in directions X, Y, and Z. In the next Step 123, a trigger signal is applied to the timing pulse generator 6, which then generates a timing pulse. The timing pulse is applied to the sample-hold circuits 421a to 423a and 52 as well as to the A/D converters 421b to 423b and 52b. In Step 124, with the uniform magnetic field in a certain direction, for example in the direction X, digital values converted from the output values V_{0X} to V_{3X} of the magnetic field measuring circuits 20 to 23 are fetched by the processor 31. In Step 125, it is judged whether or not all data for the three directions of the uniform magnetic field have been fetched. If they have not yet been fetched (NO), the Step 122 is repeated. If they have been fetched (YES), Step 126 is carried out. In the Step 126, based on the fetched digital data for the three directions, the equation (11) is evaluation to find the gains values b_1, b_2, and b_3 to be set in the variable gain amplifiers 411 to 413.

Figure 13 shows the operation sequences of removing magnetic noise. In Step 131, a trigger signal is applied to the timing pulse generator 6, which then generates a timing pulse. The timing pulse is input in to the sample-hold circuits 421a to 423a and 52a as well as the A/D converters 421b to 423b and 52b. In Step 132, digital values converted from output values V_0 to V_3 of the magnetic field measuring circuits 20 to 23 are fetched by the processor 31. In Step 133, the gain values b_1, b_2, and b_3 that have been derived in the Step 126 to be set in the variable gain amplifiers 411 to 413 are used to derive a weighted sum of the output values V_1 to V_3 of the magnetic field measuring circuits 21 to 23. The sum is subtracted from the

output value V_0 of the magnetic field measuring circuit 20, i.e., the noise is removed from the output value V_0 of the magnetic field measuring circuit 20. Accordingly, a signal with no noise is output to the D/A converter 55 in Step 134. The D/A converter converts the signal into an analog signal, which is output from the magnetic noise eliminating circuit 30.

Figure 14 shows an embodiment according to the second aspect of the invention. In the embodiments of the first aspect (Figs. 4, 5, 8, 9 and 10), the magnetic noise eliminating circuit 30 subtracts a sum of magnetic noise components from a detected value of a magnetic field of an object to be measured. A difference of the embodiment of the second aspect of Fig. 14 is that a magnetic noise eliminating circuit 300 derives a sum of the magnetic noise components and feeds the resultant sum back to a magnetic field measuring circuit for detecting the magnetic field of a measured object. The magnetic field measuring circuit are connected with a gradiometer 10 and another feed back coil magnetically connected with the pickup coil 10. According to the fed back sum, the other coil cancels the noise due to the uniform magnetic field intersecting the gradiometer 10.

Figure 15 shows the details of the magnetic noise eliminating circuit 300 according to the second aspect of the invention. The magnetic noise eliminating circuit 300 comprises variable gain amplifiers 411 to 413 that are the same as those explained before, and an addition and subtraction circuit 56. The addition and subtraction circuit 56 comprises an addition circuit 51 having, similar to that shown in Fig. 8, resistors R_1 to R_4 and an operational amplifier 51a; a feedback coil 56a magnetically engaging with a superconducting ring having a Josephson junction; a variable resistor 56b acting as current converting means for feeding a current proportional to an output of the addition circuit 51 to the feedback coil 56a; and a switch 56c for preventing a current from flowing from the variable resistor 56b to the feedback coil 56a in finding weight factors.

An adjusting operation of the embodiment will be explained next. Firstly, the switch 56c is disconnected to open a feedback loop, and the values b_1, b_2 and b_3 are calculated in the similar manner as in the previous embodiments. The values b_1, b_2, and b_3 are set as the gains of the variable gain amplifiers 411 to 413, respectively. Thereafter, a uniform magnetic field is applied to that an output of the magnetic field measuring circuit 20 reaches a maximum value. In this state, the switch 56c is connected, and the variable resistor 56b is set to zero the output of the magnetic field measuring circuit 20.

Figure 16 shows a modification of the embodiment of Fig. 15. The arrangement of this embodiment is similar to that of Fig. 15. Therefore, like parts are represented with like numerals to omit the explanations thereof. The difference of the embodiment of Fig. 16 from that of Fig. 15 will be explained next. An output of the addition circuit 51 is fed back to a feedback coil 200b magnetically engaging with a SQUID (a superconducting ring) 200a of a magnetic field measuring circuit 200. The SQUID 200a includes a Josephson element to cancel magnetic flux from a uniform magnetic field intersecting the SQUID 200a. The adjusting operation of this embodiment is the same as that of the embodiment of Fig. 15. Namely, a switch 56c is disconnected to open a feedback loop, and the values b_1, b_2, and b_3 ar obtained in a similar manner. The values b_1, b_2, and b_3 are set as the gains of variable gain amplifiers 411 to 413, respectively. Thereafter, a uniform magnetic field is applied so that the output of the magnetic field measuring circuit 200 reaches a maximum value. In this state, the switch 56c is connected, and the variable resistor 56b is set to zero the output of the magnetic field measuring circuit 200. Numeral 200c denotes a magnetic field measuring circuit, and 200d a voltage-current converting circuit.

Figure 17 shows an embodiment of a multichannel magnetic field measuring apparatus employing the magnetic field measuring apparatuses according to the first aspect of the invention, for simultaneously measuring a magnetic field at n locations.

This apparatus comprises a set of compensation coils 11, 12, and 13, magnetic field detectors 21, 22, and 23 for detecting a magnetic field through the compensation coils, gradiometers 101 to 10n disposed for respective channels, magnetic field detectors 201 to 20n for detecting a magnetic field through the pickup coils, first variable gain amplifiers 421, 422, and 423 up to "n"th variable gain amplifiers 42(3n-2), 42(3n-1), and 42(3n) for amplifying outputs of the magnetic field detectors 21, 22, and 23 respectively, and differential amplifiers 401 to 40n for subtracting a sum of the outputs of the magnetic field detectors 21, 22, and 23 multiplied by weight factors by the variable gain amplifiers 421 to 42(3n) from the outputs of the magnetic field detectors 201 to 20n, channel by channel. When a uniform magnetic field is applied successively to orthogonal axes X, Y, and Z, the magnetic field detector 21 provides outputs V_{1X} V_{1Y}, and V_{1Z} the magnetic field detector 22 provides outputs V_{2X}, V_{2Y} and V_{2Z}, the magnetic field detector 23 provides outputs V_{3X}, V_{3Y}, and V_{3Z} and the magnetic field detectors 201 to 20n of the respective channels provides outputs V_{201X}, V_{201Y}, and V_{201Z} to V_{20nX}, V_{20nY}, and V_{20nZ}. These outputs are measured, and the gains of the variable gain amplifiers of the respective channels are found and set according to the equations (11), thereby eliminating noise components due to the uniform magnetic field from the outputs of the respective channels.

Supposing the values of gains to be set in the "n"th channel of gain amplifiers 42(3n-2), 42(3n-1) and 42(3n) are b_{1n}, b_{2n}, and b_{3n} respectively, they are found from the following equations (12):

$$b_{1n}V_{1X}+b_{2n}V_{2X}+b_{3n}V_{3X}=V_{20nX}$$
$$b_{1n}V_{1Y}+b_{2n}V_{2Y}+b_{3n}V_{3Y}=V_{20nY}$$
$$b_{1n}V_{1Z}+b_{2n}V_{2Z}+b_{3n}V_{3Z}=V_{20nZ} \qquad (12)$$

Figure 18 shows an arrangement of probes 60 in the multichannel magnetic field measuring apparatus of Fig. 17. Since only one compensation coil supporting material 63 is necessary, the material 63 is arranged for the central one of n probes 60. The material 63 is the same as that shown in Fig. 6A. The other probes 60 have only cooling holes 66 formed on pickup coil supporting materials.

Figure 19 shows an embodiment for measuring a magnetic field at m locations, employing magnetic field detectors according to the second aspect of the invention. In this embodiment, a set of compensation coils 11, 12, and 13 and a magnetic noise eliminating circuit 301 to 30m operate a sum of magnetic noise components. The resultant sum of the magnetic noise components is fed back to coils magnetically engaging with gradiometers 101 to 10m located at m positions respectively to cancel the magnetic noise of a uniform magnetic field intersecting the gradiometers 101 to 10m.

The magnetic field detectors 20 to 23 of the above embodiments are not necessarily required to be made of superconducting materials.

Claims

1. An apparatus for measuring a very weak magnetic field generated by for example a human body, comprising:-

   a gradiometer (10; 101, 102, ... 10n);

   a magnetic field measuring circuit (20; 201, 202, ... 20n) for measuring a magnetic field from an output signal of said gradiometer (10);

   at least three compensation coils (11, 12, 13, ...) for detecting a uniform magnetic field or a uniform gradient magnetic field existing around said gradiometer (10), said three compensation coils (11, 12, 13) being oriented in three different directions that are not all in the same plane;

   at least three magnetic field measuring circuits (21, 22, 23, ...) for measuring magnetic fields in respective ones of said directions according to output signals of said compensation coils (11, 12, 13, ...); and

   a magnetic noise eliminating circuit (30; 301, 302, ... 30n) for eliminating magnetic noise from the output signal of said gradiometer (10; 101, 102, ... 10n) by using the output signals of said three magnetic field measuring circuits (21, 22, 23, ...);

   characterised in that:-

   sensitivity values of said three magnetic field measuring circuits (21, 22, 23, ...) are individually set in advance by applying, to said compensation coils (11, 12, 13, ...) and said gradiometer, uniform magnetic fields ($\underline{H}_1$, $\underline{H}_2$, $\underline{H}_3$) in three different directions that are not all in the same plane and by solving equations of the following form:-

$$b_1V_{1x} + b_2V_{2x} + b_3V_{3x} = V_{0x}$$
$$b_1V_{1y} + b_2V_{2y} + b_3V_{3y} = V_{0y}$$
$$b_1V_{1z} + b_2V_{2z} + b_3V_{3z} = V_{0z}$$

   where x, y, z represent said three different directions b_1, b_2 and b_3 represent said sensitivity values of the magnetic field measuring circuits, V_1, V_2 and V_3 represent the output signals of said compensation coils and V_0 represents the output signal of said gradiometer;

   whereby a mutually-orthogonal orientation of said compensation coils (11, 12, 13, ...) is not necessary.

2. An apparatus according to claim 1, wherein said magnetic noise eliminating circuit (30) comprises:

   multiplication circuits (401, 402, 403, ...) for multiplying outputs of said magnetic field measuring circuits (21, 22, 23,...) by predetermined factors to weight the outputs; and

   an addition and subtraction circuit (5) for finding, from outputs of said multiplication circuits (401, 402, 403, ...), magnetic noise components caused by the uniform magnetic field or the uniform gradient magnetic field existing around said pickup coil (10), and subtracting the magnetic noise components

from an output of said magnetic field measuring circuit (20).

3. An apparatus according to claim 2, wherein said magnetic field measuring circuits (21, 22, 23,...) are superconducting quantum interference devices respectively, said multiplication circuits (401, 402, 403,...) are variable gain amplifiers (411, 412, 413, ...) for respectively amplifying outputs of said magnetic field measuring circuits (21, 22, 23,...) by predetermined weights, and said addition and subtraction circuit (5) is a differential amplifier (50).

4. An apparatus according to claim 3, wherein said pickup coil (10) is fitted to a front end of a probe (60), and a support member for supporting the compensation coils (11, 12, 13,...) is substantially coaxially fitted to the probe (60).

5. An apparatus according to claim 4, wherein said pickup coil (10) is formed on said probe (60) by lithography.

6. An apparatus according to claim 3, wherein said differential amplifier (50) comprises:
a first adder (51) for adding outputs of said variable gain amplifiers (411, 412, 413,...) to each other, inverting the added result, and outputting the added result;
a second addition circuit (52) for adding the inverted output of said first addition circuit (51) to an output of said magnetic field measuring circuit (20), and inverting and outputting the added result; and
an inverting amplifier circuit (53) for inverting and outputting an output of said second addition circuit (52).

7. An apparatus according to claim 3, wherein said differential amplifier (50) comprises:
sample-hold circuits (421a, 422a, 423a, ..., 54a) for sampling and holding outputs of said magnetic measuring circuits (21, 22, 23,..., 20) respectively;
A/D converters (421b, 422b, 423b, ..., 54b) for converting analog outputs of said sample-hold circuits (421a, 422a, 423a,..., 54a) into digital signals respectively;
a timing pulse generator (6) for generating operation timing pulses for said sample-hold circuits (421a, 422a, 423a,..., 54a) and A/D converters (421b, 422b, 423b,..., 54b);
registers (421d, 422d, 423d) for holding the predetermined weight factors;
multipliers (421c, 422c, 423c) for multiplying outputs of said A/D converters (421b, 422b, 423b) by the factors held in said registers (421d, 422d, 423d); and
an adder (54c) for adding outputs of said multipliers (421c, 422c, 423c) to each other and subtracting the added result from an output of said A/D converter (54b).

8. An apparatus according to claim 3, wherein said differential amplifier (50) comprises:
sample-hold circuits (421a, 422a, 423a, ..., 54a) for sampling and holding outputs of said magnetic field measuring circuits (21, 22, 23,..., 20) respectively;
A/D converters (421b, 422b, 423b, ..., 54b) for converting analog outputs of said sample-hold circuits (421a, 422a, 423a,..., 54a) into digital signals respectively;
a timing pulse generator (6) for generating operation timing pulses for said sample-hold circuits (421a, 422a, 423a,..., 54a) and A/D converters (421b, 422b, 423b,..., 54b); and
a processor (31) for fetching outputs of said A/D converters (421b, 422b, 423b), weighting the fetched outputs and then adding them to each other, fetching an output of said A/D converter (54b), and subtracting therefrom the added result.

9. An apparatus according to any preceding claim, having:-
n said gradiometers (101, 102, ..., 10n);
n said magnetic field measuring circuits (201, 202, ..., 20n) connected to said n gradiometers (101, 102, ..., 10n), respectively; and
n said magnetic noise eliminating circuits connected to respective ones of said n gradiometers (101, 102, ..., 10n), which commonly receive outputs of said three magnetic field measuring circuits (21, 22, 23) and eliminate magnetic noise using individual respective sensitivity values (b_{11}, b_{12}, ... b_{1n}; b_{21}, b_{22}, ... b_{3n}) obtained for each respective one of said n magnetic field measuring circuits (201, 202, ..., 20n).

10. An apparatus according to claim 1, wherein said magnetic noise eliminating circuit (300) eliminates magnetic noise by feeding to said gradiometer (10), the scalar products of weight vectors incorporating said sensitivity values (b_1, b_2, b_3) of said magnetic field measuring circuits (21, 22, 23, ...), and measured vectors containing, as vector components, the magnetic fields detected by said magnetic field measuring circuits (21, 22, 23, ...), so as to generate a compensating magnetic field.

11. An apparatus according to claim 10, wherein said magnetic noise eliminating circuit (300) comprises:-
variable gain amplifiers (411, 412, 413, ...) for amplifying outputs of said magnetic field measuring circuits (21, 22, 23, ...) by the predetermined weights;
an addition circuit (56) for adding outputs of said variable gain amplifiers (411, 412, 413, ...) to each other;
a feedback coil (56a) magnetically connected to said gradiometer (10);
current converting means (56b) for feeding a current proportional to an output of said addition circuit (56) to said feedback coil (56a); and
current blocking means (56c) for preventing a flow of a current from said current converting means (56b) to said feedback coil (56a), when finding the weight factors.

12. An apparatus according to claim 11, wherein said magnetic field measuring circuits (21, 22, 23, ...) comprise superconducting quantum interference devices, and said feedback coil (56a) is magnetically connected to said superconducting quantum interference devices.

13. An apparatus according to claim 11 or 12, comprising:-
n said gradiometers (101, 102, ..., 10n);
n said magnetic field measuring circuits (201, 202, ..., 20n) connected to said n gradiometers (101, 102, ..., 10n), respectively; and
n said magnetic noise eliminating circuits (301, 302, ... 30n) which feed back to respective ones of said n gradiometers (101, 102, ... 10n) said scalar products obtained using individual sensitivity values (b_{11}, b_{12}, ... b_{1n}; b_{21}, b_{22} ..... b_{3n}) for each respective magnetic field measuring circuit.

Patentansprüche

1. Vorrichtung zum Messen sehr schwacher Magnetfelder, die beispielweise durch einen menschlichen Körper erzeugt werden, umfassend:
einen Gradientenmesser (10; 101, 102, ... 10n),
eine magnetfeldmessende Schaltung (20; 201, 202, ... 20n) zum Messen eines Magnetfeldes von dem Ausgangssignal des Gradientenmessers (10),
mindestens drei Kompensationsspulen (11, 12, 13, ...) zur Erfassung eines gleichförmigen Magnetfeldes oder eines gleichförmigen magnetischen Gradientenfeldes, das in der Umgebung des Gradientenmessers (10) vorhanden ist, wobei die drei Kompensationsspulen (11, 12, 13) in drei unterschiedliche Richtungen, die alle nicht in derselben Ebene liegen, orientiert sind,
mindestens drei magnetfeldmessende Schaltungen (21, 22, 23, ...) zum Messen von Magnetfeldern in den jeweiligen Einzelrichtungen gemäß den Ausgangssignalen der Kompensationsspulen (11, 12, 13, ...) und
eine Schaltung zur magnetischen Rauschunterdrückung (30, 301, 302, ... 30n) zur Eliminierung magnetischen Rauschens von dem Ausgangssignal des Gradientenmessers (10; 101, 102, ... 10n) unter Verwendung der Ausgangssignale der drei magnetfeldmessenden Schaltungen (21, 22, 23, ...),
dadurch gekennzeichnet, daß
Empfindlichkeitswerte der drei magnetfeldmessenden Schaltungen (21, 22, 23, ...) einzeln im voraus festgelegt werden, indem gleichförmige Magnetfelder ($\underline{H}_1$, $\underline{H}_2$, $\underline{H}_3$) in drei unterschiedlichen Richtungen, die alle nicht in derselben Ebene liegen, auf die Kompensationsspulen (11, 12, 13, ...) und den Gradientenmesser angewendet und die Gleichungen der folgenden Form gelöst werden:

$$b_1 V_{1x} + b_2 V_{2x} + b_3 V_{3x} = V_{0x}$$
$$b_1 V_{1y} + b_2 V_{2y} + b_3 V_{3y} = V_{0y}$$
$$b_1 V_{1z} + b_2 V_{2z} + b_3 V_{3z} = V_{0z},$$

wobei x, y, z die drei unterschiedlichen Richtungen darstellen, b_1, b_2 und b_3 die Empfindlichkeitswerte der magnetfeldmessenden Schaltungen wiedergeben, V_1, V_2 und V_3 die Ausgangssignale der Kompen-

sationsspulen vorstellen und V_0 das Ausgangssignal des Gradientenmessers verkörpern,
wodurch eine wechselseitige orthogonale Orientierung der Kompensationsspulen (11, 12, 13, ...) nicht notwendig ist.

2. Vorrichtung nach Anspruch 1, wobei die Schaltung zur magnetischen Rauschunterdrückung (30) umfaßt:
Multiplikationsschaltungen (401, 402, 403. ...) zum Multiplizieren der Ausgangssignale der magnetfeldmessenden Schaltungen (21, 22, 23, ...) mit vorbestimmten Faktoren, um die Ausgangssignale zu wichten und
eine Additions- und Subtraktionsschaltung (5), um aus den Ausgangssignalen der Multiplikationsschaltungen (401, 402, 403, ...) magnetische Rauschkomponenten herauszufinden, die durch das gleichförmige Magnetfeld oder das gleichförmige magnetische Gradientenfeld, das um die Aufnehmerspule (10) vorhanden ist, verursacht werden und zum Subtrahieren der magnetischen Rauschkomponenten von einem Ausgangssignal der magnetfeldmessenden Schaltung (20).

3. Vorrichtung nach Anspruch 2, bei der die magnetfeldmessenden Schaltungen (21, 22, 23, ...) jeweils supraleitende Quanteninterferenzeinrichtungen sind, die Multiplikationsschaltungen (401, 402, 403, ...) Verstärker mit variabler Verstärkung (411, 412, 413, ...) zum entsprechenden Verstärken der Ausgangssignale der magnetfeldmessenden Schaltungen (21, 22, 23, ...) durch vorbestimmte Wichtungen sind und die Additions- und Subtraktionsschaltung (5) ein Differenzverstärker (50) ist.

4. Vorrichtung nach Anspruch 3, bei der die Aufnehmerspule (10) in das vordere Ende eines Meßfühlers (60) eingepaßt ist und ein Trägerteil zum Tragen der Kompensationsspulen (11, 12, 13, ...) im wesentlichen koaxial in den Meßfühler (60) eingepaßt ist.

5. Vorrichtung nach Anspruch 4, wobei die Aufnehmerspule (10) durch Lithographie auf dem Meßfühler (60) ausgebildet ist.

6. Vorrichtung nach Anspruch 3, wobei der Differenzverstärker (50) umfaßt:
einen ersten Addierer (51) zum Addieren der Ausgangssignale der Verstärker mit variabler Verstärkung (411, 412, 413 ...) mit einander, zum Invertieren des addierten Ergebnisses und zum Ausgeben des addierten Ergebnisses,
eine Zweite Additionsschaltung (52) zum Addieren des invertierten Ausgangsignals der ersten Additionsschaltung (51) mit einem Ausgangssignal der magnetfeldmessenden Schaltung (20) und zum Invertieren und Ausgeben des addierten Ergebnisses und
eine invertierende Verstärkerschaltung (53) zum Invertieren und Ausgeben eines Ausgangssignals der zweiten Additionsschaltung (52).

7. Vorrichtung nach Anspruch 3, wobei der Differenzverstärker (50) umfaßt:
Abtast-Halteschaltungen (421a, 422a, 423a, ..., 54a) zum Abtasten und Halten der Ausgangssignale der jeweiligen magnetfeldmessenden Schaltungen (21, 22, 23, ..., 20)
A/D-Wandler (421b, 422b, 423b, ..., 54b) zum Umwandeln analoger Ausgangssignale der Abtast-Halteschaltungen (421a, 422a, 423a, ..., 54a) in entsprechende digitale Signale,
einen Taktgeber (6) zum Erzeugen eines Operations-Steuerimpulses für die Abtast-Halteschaltungen (421a, 422a, 423a, ..., 54a) und die A/D-Wandler (421b, 422b, 423b, ..., 54b),
Register (421d, 422d, 423d) zum Speichern der vorbestimmten Wichtungsfaktoren,
Multiplizierer (421c, 422c, 423c) zum Multiplizieren der Ausgangssignale der A/D-Wandler (421b, 422b, 423b) mit den Faktoren, die in den Registern (421d, 422d, 423d) gespeichert sind und
einen Addierer (54c) zum Addieren der Ausgangssignale der Multiplizierer (421c, 422c, 423c) miteinander und zum Subtrahieren des addierten Ergebnisses von einem Ausgangssignal des A/D-Wandlers (54b).

8. Vorrichtung nach Anspruch 3, wobei der Differenzverstärker (50) umfaßt:
Abtast-Halteschaltungen (421a, 422a, 423a, ..., 54a) zum Abtasten und Halten der Ausgangssignale der jeweiligen magnetfeldmessenden Schaltungen (21, 22, 23, ..., 20)
A/D-Wandler (421b, 422b, 423b, ..., 54b) zum Umwandeln analoger Ausgangssignale der Abtast-Halteschaltungen (421a, 422a, 423a, ..., 54a) in entsprechende digitale Signale,
einen Taktgeber (6) zum Erzeugen eines Operations-Steuerimpulses für die Abtast-Halteschaltun-

gen (421a, 422a, 423a, ..., 54a) und die A/D-Wandler (421b, 422b, 423b, ..., 54b) und
einen Prozessor (31) zum Erfassen der Ausgangssignale der A/D-Wandler (421b, 422b, 423b), der die erfaßten Ausgangssignale wichtet und sie dann miteinander addiert und der das Ausgangssignal des A/D-Wandlers (54b) erfaßt und von den addierten Ergebnis subtrahiert.

9. Vorrichtung nach einem der vorhergehenden Ansprüche, mit
n Gradientenmessern (101, 102, ..., 10n),
n magnetfeldmessenden Schaltungen (201, 202, ...,20n), verbunden mit dem jeweiligen der n Gradientenmesser (101, 102, ..., 10n) und
n Schaltungen zur magnetischen Rauschunterdrückung, die mit dem entsprechenden der n Gradientenmesser (101, 102, ..., 10n) verbunden sind, die gewöhnlich Ausgangssignale der drei magnetfeldmessenden Schaltungen (21, 22, 23) empfangen und das magnetische Rauschen unter Verwendung jeweils einzelner Empfindlichkeitswerte (b_{11}, b_{12}, ... b_{1n}; b_{21}, b_{22}, ... b_{3n}), die für jeden der entsprechenden n magnetfeldmessenden Schaltungen (201, 202, ...,20n) erhalten werden, eliminieren.

10. Vorrichtung nach Anspruch 1, wobei die Schaltung zur magnetischen Rauschunterdrückung (300) magnetisches Rauschen eliminiert, indem der Gradientenmesser (10) mit den Skalarprodukten der Wichtungsvektoren versorgt wird, die die Empfindlichkeitswerte (b_1, b_2 und b_3) der magnetfeldmessenden Schaltungen (21, 22, 23, ...) und die gemessenen Vektoren einschließen, die als Vektorkomponenten die Magnetfelder enthalten, die durch die magnetfeldmessenden Schaltungen (21, 22, 23, ...) gemessen wurden, so daß ein Kompensationsmagnetfeld erzeugt wird.

11. Vorrichtung nach Anspruch 10, bei der die Schaltung zur magnetischen Rauschunterdrückung (300) umfaßt:
Verstärker mit variabler Verstärkung (411, 412, 413, ...) zum entsprechenden Verstärken der Ausgangssignale der magnetfeldmessenden Schaltungen (21, 22, 23, ...) durch vorbestimmte Wichtungen,
eine Additionsschaltung (56) zum Addieren der Ausgangssignale der Verstärker mit variabler Verstärkung (411, 412, 413, ...) miteinander,
eine Rückkopplungsspule (56a), die magnetisch mit dem Gradientenmesser (10) gekoppelt ist,
stromconvertierende Mittel (56b) zum zuführen eines Stroms proportional zu einem Ausgangssignal der Additionsschaltung (56) zu der Rückkopplungsspule (56a) und
stromblockierende Mittel (56c) zum Verhindern eines Stromflusses von den strominvertierenden Mitteln (56b) zu der Rückkopplungsspule (56a), beim Auffinden der Wichtungsfaktoren.

12. Vorrichtung nach Anspruch 11, bei der die magnetfeldmessenden Schaltungen (21, 22, 23, ...) supraleitende Quanteninterferrometer enthalten und die Rückkopplungsspule (56a) magnetisch mit den supraleitenden Quanteninterferenzeinrichtungen gekoppelt ist.

13. Vorrichtung nach Anspruch 11 oder 12, umfassend:
n Gradientenmesser (101, 102, ..., 10n),
n magnetfeldmessende Schaltungen (201, 202, ..., 20n), verbunden mit dem jeweiligen der n Gradientenmesser (101, 102, ..., 10n) und
n Schaltungen zur magnetischen Rauschunterdrückung (301, 302, ..., 30n), die zu den entsprechenden n Gradientenmessern (101, 102, ..., 10n) jene Skalarprodukte rückkoppeln, die unter Verwendung einzelner Empfindlichkeitswerte (b_{11}, b_{12}, ... b_{1n}; b_{21}, b_{22}, ... b_{3n}) für jede entsprechende magnetfeldmessende Schaltung erhalten werden.

Revendications

1. Appareil de mesure d'un champ magnétique très faible, créé par exemple par un corps humain, comprenant :
un gradiomètre (10 ; 101, 102,... 10n),
un circuit (20 ; 201, 202,... 20n) de mesure d'un champ magnétique à partir d'un signal de sortie du gradiomètre (10),
au moins trois bobines de compensation (11, 12, 13...) destinées à détecter un champ magnétique uniforme ou un champ magnétique de gradient uniforme existant autour du gradiomètre (10), les trois bobines de compensation (11, 12, 13) étant orientées dans trois directions différentes qui ne se

trouvent pas toutes dans le même plan,

au moins trois circuits de mesure de champ magnétique (21, 22, 23...) destinés à mesurer les champs magnétiques dans les directions respectives en fonction des signaux de sortie des bobines de compensation (11, 12, 13...), et

un circuit (30 ; 301, 302,... 30n) destiné à éliminer le bruit magnétique du signal de sortie du gradiomètre (10 ; 101, 102,... 10n) par utilisation des signaux de sortie des trois circuits de mesure (21, 22, 23...) de champ magnétique,

caractérisé en ce que

les valeurs des sensibilités des trois circuits (21, 22, 23...) de mesure de champ magnétique sont réglées individuellement au préalable par application, aux bobines de compensation (11, 12, 13...) et au gradiomètre, de champs magnétiques uniformes ($\underline{H}_1$, $\underline{H}_2$, $\underline{H}_3$) dans trois directions différentes qui ne se trouvent pas toutes dans le même plan, et par solution des équations de la forme suivante

$$b_1 V_{1X} + b_2 V_{2X} + b_3 V_{3X} = V_{0X}$$
$$b_1 V_{1Y} + b_2 V_{2Y} + b_3 V_{3Y} = V_{0Y}$$
$$b_1 V_{1Z} + b_2 V_{2Z} + b_3 V_{3Z} = V_{0Z}$$

x, y, z représentant trois directions différentes, b_1, b_2 et b_3 représentant les valeurs de sensibilité des circuits de mesure de champ magnétique, V_1, V_2 et V_3 représentant les signaux de sortie des bobines de compensation, et V_0 représentant le signal de sortie du gradiomètre,

si bien qu'une orientation des bobines de compensation (11, 12, 13...) en directions mutuellement orthogonales n'est pas nécessaire.

2. Appareil selon la revendication 1, dans lequel le circuit (30) d'élimination de bruit magnétique comprend :

des circuits (401, 402, 403...) de multiplication des signaux de sortie des circuits (21, 22, 23...) de mesure de champ magnétique par des facteurs prédéterminés pour la pondération des signaux de sortie, et

un circuit (5) d'addition et de soustraction destiné à déterminer, à partir des signaux de sortie des circuits de multiplication (401, 402, 403...), des composantes du bruit magnétique dû au champ magnétique uniforme ou au champ magnétique de gradient uniforme existant autour de la bobine de capteur (10), et à soustraire les composantes de bruit magnétique d'un signal de sortie du circuit (20) de mesure de champ magnétique.

3. Appareil selon la revendication 2, dans lequel les circuits (21, 22, 23...) de mesure de champ magnétique sont des dispositifs interférentiels quantiques supraconducteurs respectivement, les circuits de multiplication (401, 402, 403...) sont des amplificateurs à gain variable (411, 412, 413...) destinés à amplifier respectivement les signaux de sortie des circuits (21, 22, 23...) de mesure de champ magnétique par des poids prédéterminés, et le circuit (5) d'addition et de soustraction est un amplificateur différentiel (50).

4. Appareil selon la revendication 3, dans lequel la bobine (10) de capteur est montée à une extrémité avant d'une sonde (60), et un organe de support des bobines de compensation (11, 12, 13...) est monté en position pratiquement coaxiale à la sonde (60).

5. Appareil selon la revendication 4, dans lequel la bobine (10) de capteur est formée sur la sonde (60) par lithographie.

6. Appareil selon la revendication 3, dans lequel l'amplificateur différentiel (50) comprend :

un premier additionneur (51) destiné à ajouter les signaux de sortie des amplificateurs à gain variable (411, 412, 413...) les uns aux autres, à inverser le résultat additionné, et à transmettre le résultat ajouté,

un second circuit d'addition (52) destiné à ajouter le signal inversé de sortie du premier circuit d'addition (51) à un signal de sortie du circuit (20) de mesure de champ magnétique et à inverser et transmettre le signal ajouté, et

un circuit amplificateur inverseur (53) destiné à inverser et transmettre un signal de sortie du second circuit d'addition (52).

7. Appareil selon la revendication 3, dans lequel l'amplificateur différentiel (50) comporte :
des circuits (421a, 422a, 423a,... 54a) d'échantillonnage et de maintien des signaux de sortie des circuits de mesure magnétique (21, 22, 23,... 20) respectivement,
des convertisseurs analogiques-numériques (421b, 422b, 423b,... 54b) destinés à transformer les signaux analogiques de sortie des circuits d'échantillonnage et de maintien (421a, 422a, 423a,... 54a) en signaux numériques respectivement,
un générateur (6) d'impulsions de synchronisation destiné à créer des impulsions de synchronisation du fonctionnement pour les circuits d'échantillonnage et de maintien (421a, 422a, 423a,... 54a) et les convertisseurs analogiques-numériques (421b, 422b, 423b,... 54b),
des registres (421d, 422d, 423d) destinés à conserver les facteurs prédéterminés de pondération,
des circuits multiplicateurs (421c, 422c, 423c) destinés à multiplier les signaux de sortie des convertisseurs analogiques-numériques (421b, 422b, 423b) par les facteurs contenus dans les registres (421d, 422d, 423d), et
un additionneur (54c) destiné à ajouter les signaux de sortie des circuits multiplicateurs (421c, 422c, 423c) les uns aux autres et à soustraire le résultat ajouté du signal de sortie du convertisseur analogique-numérique (54b).

8. Appareil selon la revendication 3, dans lequel l'amplificateur différentiel (50) comprend :
des circuits d'échantillonnage et de maintien (421a, 422a, 423a,... 54a) destinés à échantillonner et maintenir les signaux de sortie des circuits (21, 22, 23,... 20) respectivement de mesure de champ magnétique,
des convertisseurs analogiques-numériques (421b, 422b, 423b,... 54b) destinés à transformer les signaux analogiques de sortie des circuits d'échantillonnage et de maintien (421a, 422a, 423a,... 54a) en signaux numériques respectifs,
un générateur (6) d'impulsions de synchronisation destiné à créer des impulsions de synchronisation du fonctionnement pour les circuits d'échantillonnage et de maintien (421a, 422a, 423a,... 54a) et des convertisseurs analogiques-numériques (421b, 422b, 423b,... 54b), et
un processeur (31) destiné à déplacer les signaux de sortie des convertisseurs analogiques-numériques (421b, 422b, 423b), à pondérer les signaux déplacés de sortie puis à les ajouter les uns aux autres, à déplacer un signal de sortie du convertisseur analogique-numérique (54b) et à soustraire le résultat ajouté de celui-ci.

9. Appareil selon l'une quelconque des revendications précédentes, comprenant :
n gradiomètres (101, 102,... 10n),
n circuits de mesure de champ magnétique (201, 202,... 20n) connectés aux n gradiomètres (101, 102,... 10n) respectivement, et
n circuits éliminateurs de bruit magnétique connectés aux n gradiomètres respectifs (101, 102,... 10n) qui reçoivent en commun les signaux de sortie des trois circuits de mesure de champ magnétique (21, 22, 23) et éliminent le bruit magnétique à l'aide de valeurs individuelles respectives de sensibilité (b_{11}, b_{12},... b_{1n} ; b_{21}, b_{22},... b_{3n}) qui sont obtenues pour les circuits respectifs parmi les n circuits (201, 202,... 20n) de mesure de champ magnétique.

10. Appareil selon la revendication 1, dans lequel le circuit (300) d'élimination de bruit magnétique élimine le bruit magnétique par transmission au gradiomètre (10) des produits scalaires des vecteurs de pondération comprenant les valeurs de sensibilité (b_1, b_2, b_3) des circuits (21, 22, 23...) de mesure de champ magnétique et des vecteurs mesurés contenant, comme composantes vectorielles, des champs magnétiques détectés par les circuits (21, 22, 23...) de mesure de champ magnétique afin qu'un champ magnétique de compensation soit créé.

11. Appareil selon la revendication 10, dans lequel le circuit (300) éliminateur de bruit magnétique comprend :
des amplificateurs à gain variable (411, 412, 413...) destinés à amplifier les signaux de sortie des circuits (21, 22, 23...) de mesure de champ magnétique par les poids prédéterminés,
un circuit d'addition (56) destiné à ajouter les signaux de sortie des amplificateurs à gain variable (411, 412, 413...) les uns aux autres,
une bobine de réaction négative (56a) connectée magnétiquement au gradiomètre (10),
un dispositif (56b) de conversion de courant destinée à transmettre un courant proportionnel à une sortie du circuit d'addition (56) vers la bobine de réaction négative (56a), et

un dispositif (56c) d'arrêt de courant destiné à empêcher la circulation d'un courant du dispositif (56b) de conversion de courant vers la bobine de réaction négative (56a) lors de la détermination des facteurs de pondération.

12. Appareil selon la revendication 11, dans lequel les circuits (21, 22, 23...) de mesure de champ magnétique comprennent des dispositifs interférentiels quantiques supraconducteurs, et la bobine de réaction négative (56a) est connectée magnétiquement aux dispositifs interférentiels quantiques supraconducteurs.

13. Appareil selon la revendication 11 ou 12, comprenant :

n gradiomètres (101, 102,... 10n),

n circuits (201, 202,... 20n) de mesure de champ magnétique connectés respectivement aux n gradiomètres (101, 102,... 10n), et

n circuits éliminateurs de bruit magnétique (301, 302,... 30n) qui renvoient aux gradiomètres respectifs parmi les n gradiomètres (101, 102,... 10n) les produits scalaires obtenus à l'aide des valeurs individuelles de sensibilité (b_{11}, b_{12},... b_{1n} ; b_{21}, b_{22},... b_{3n}) pour chaque circuit respectif de mesure de champ magnétique.

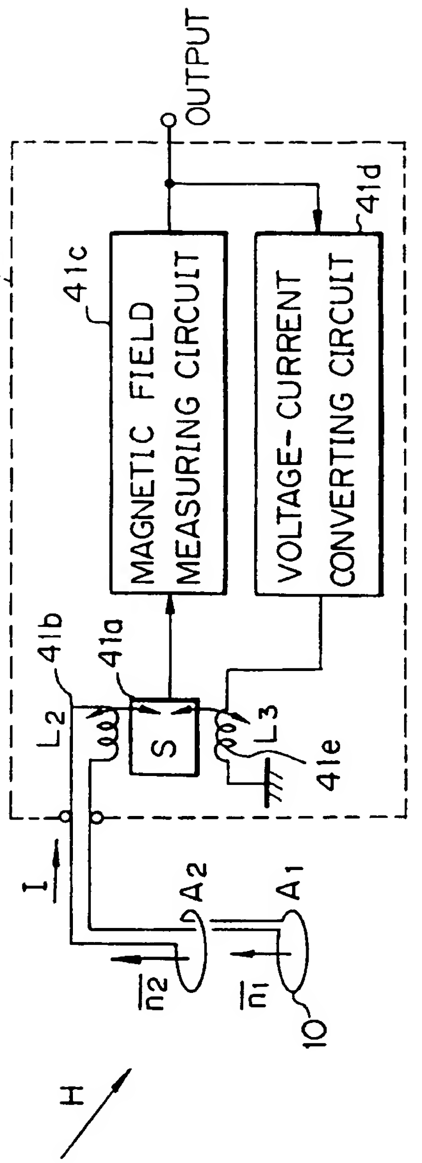

41
41c
41b
41a
41d
41e
L2
L3
S
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE-CURRENT CONVERTING CIRCUIT
OUTPUT
I
H
A2
A1
$\overline{n_2}$
$\overline{n_1}$
10

Fig. 1A

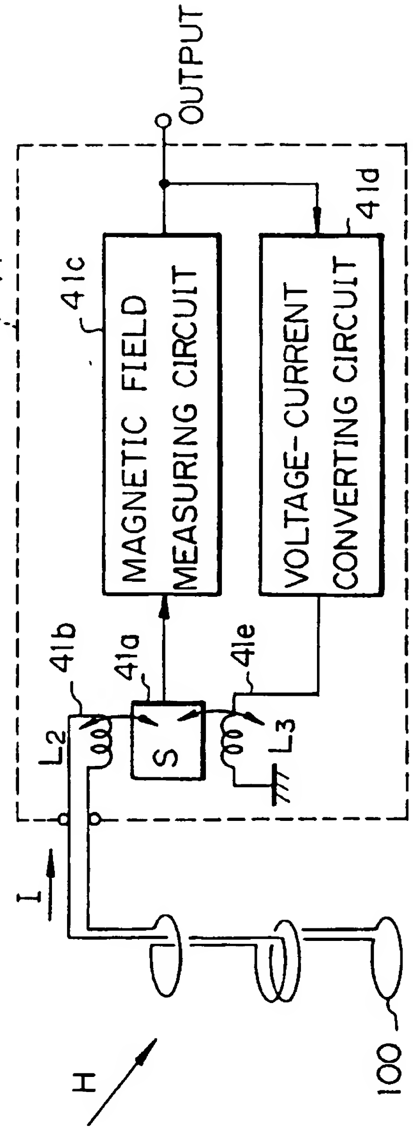

41
41c
41b
41a
41d
41e
L2
L3
S
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE-CURRENT CONVERTING CIRCUIT
OUTPUT
I
H
100

Fig. 1B

Fig. 2A

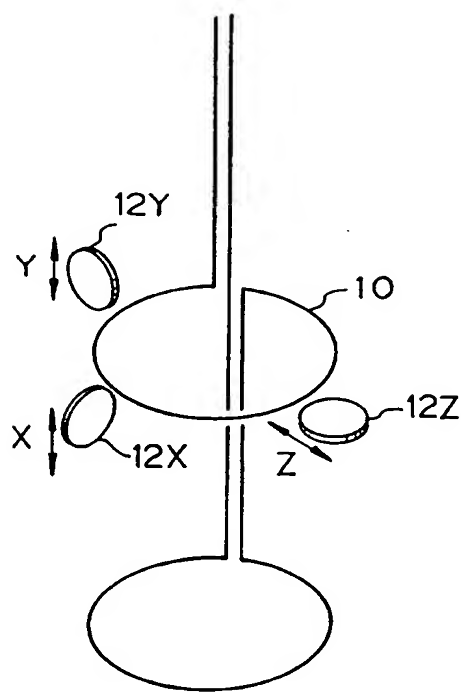


Fig. 2B

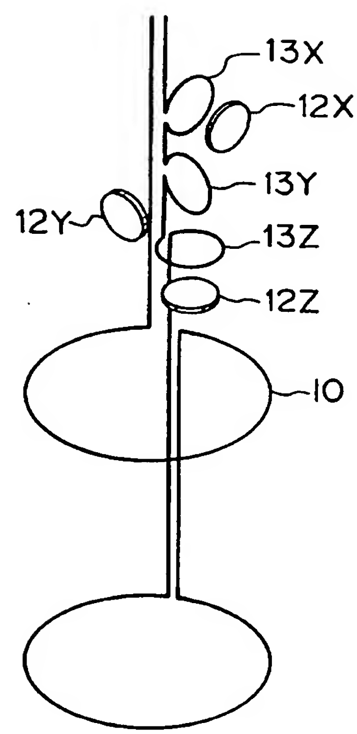


Fig. 3

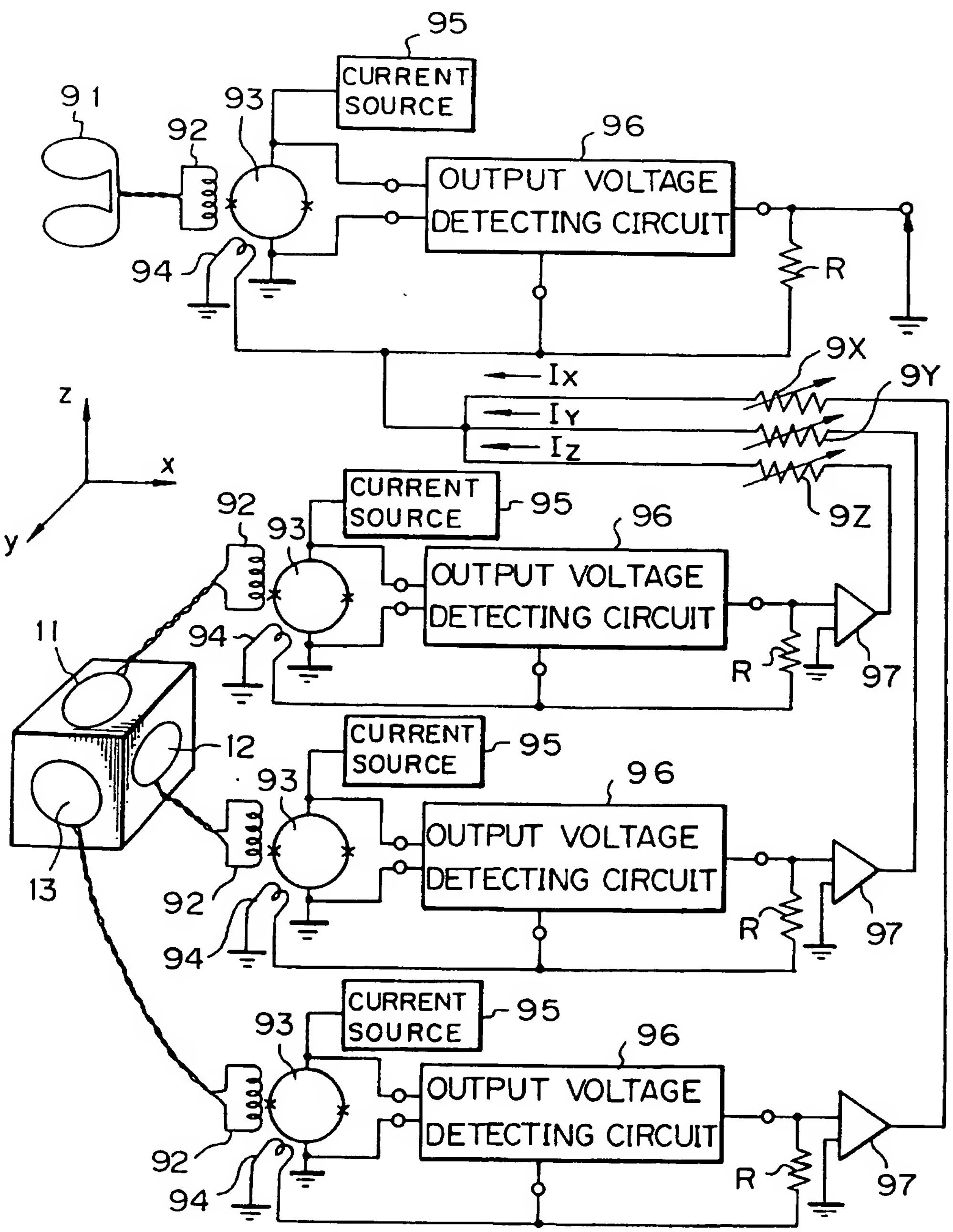
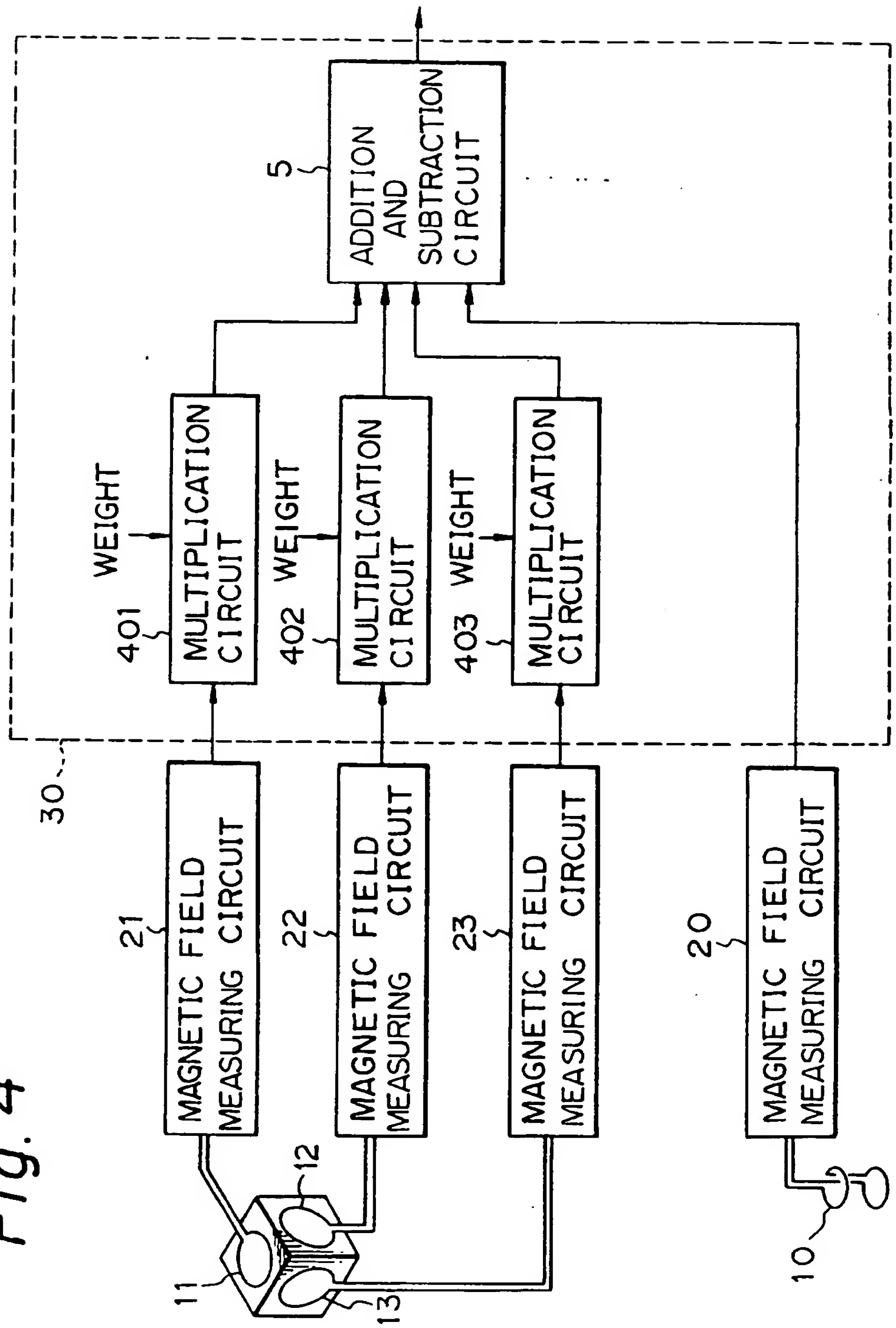

95
CURRENT SOURCE
91
92
93
96
OUTPUT VOLTAGE DETECTING CIRCUIT
94
R
9X
Ix
9Y
IY
IZ
9Z
Z
X
Y
11
12
13
97

Fig. 4


30
5
ADDITION AND SUBTRACTION CIRCUIT
401
MULTIPLICATION CIRCUIT
WEIGHT
402
MULTIPLICATION CIRCUIT
WEIGHT
403
MULTIPLICATION CIRCUIT
WEIGHT
21
MAGNETIC FIELD MEASURING CIRCUIT
22
MAGNETIC FIELD MEASURING CIRCUIT
23
MAGNETIC FIELD MEASURING CIRCUIT
20
MAGNETIC FIELD MEASURING CIRCUIT
11
12
13
10

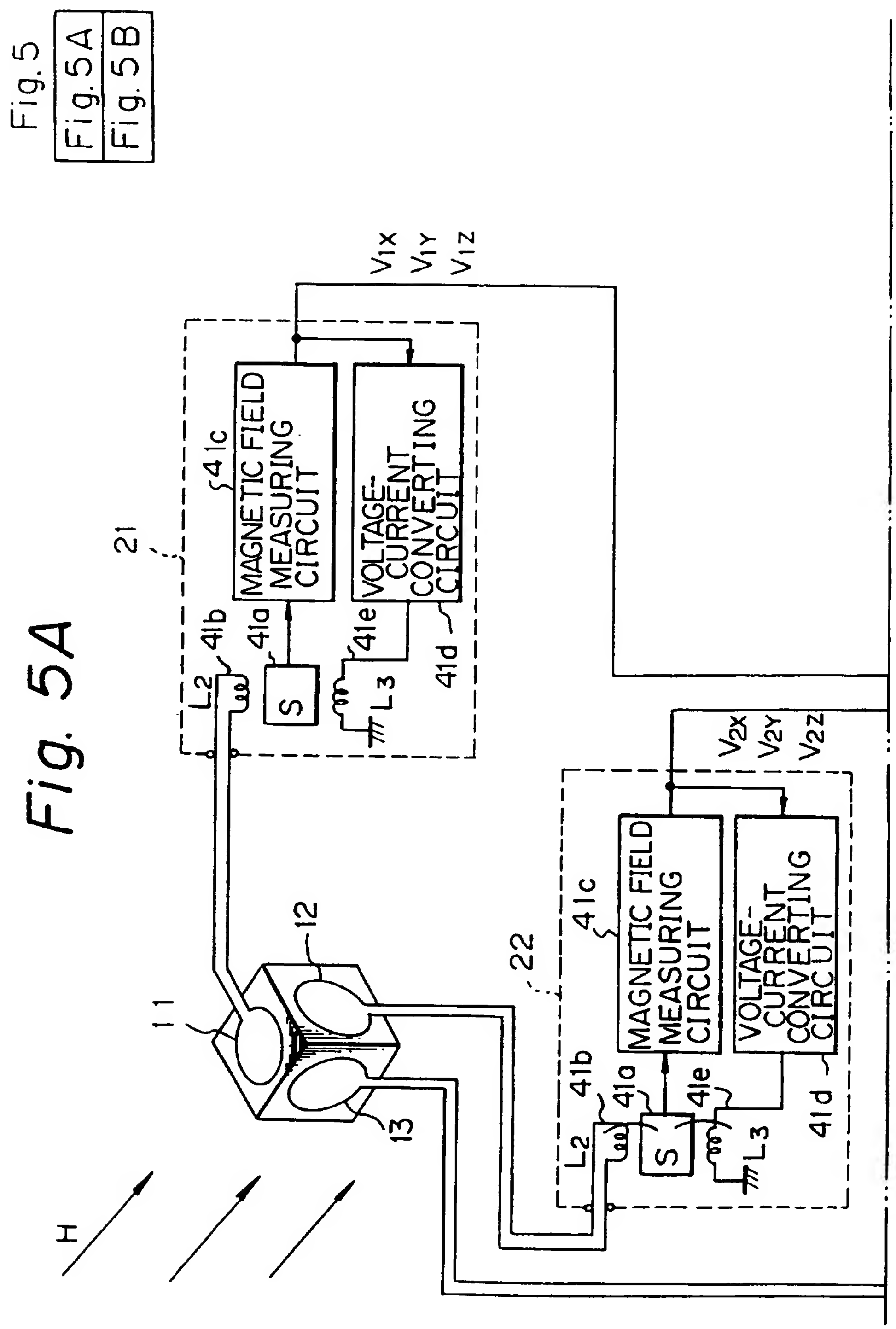


Fig. 5
Fig. 5A
Fig. 5B
H
11
12
13
21
22
L2
41b
41a
S
41e
L3
41d
41c
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE-CURRENT CONVERTING CIRCUIT
V1X
V1Y
V1Z
V2X
V2Y
V2Z

Fig. 5A

Fig. 5B

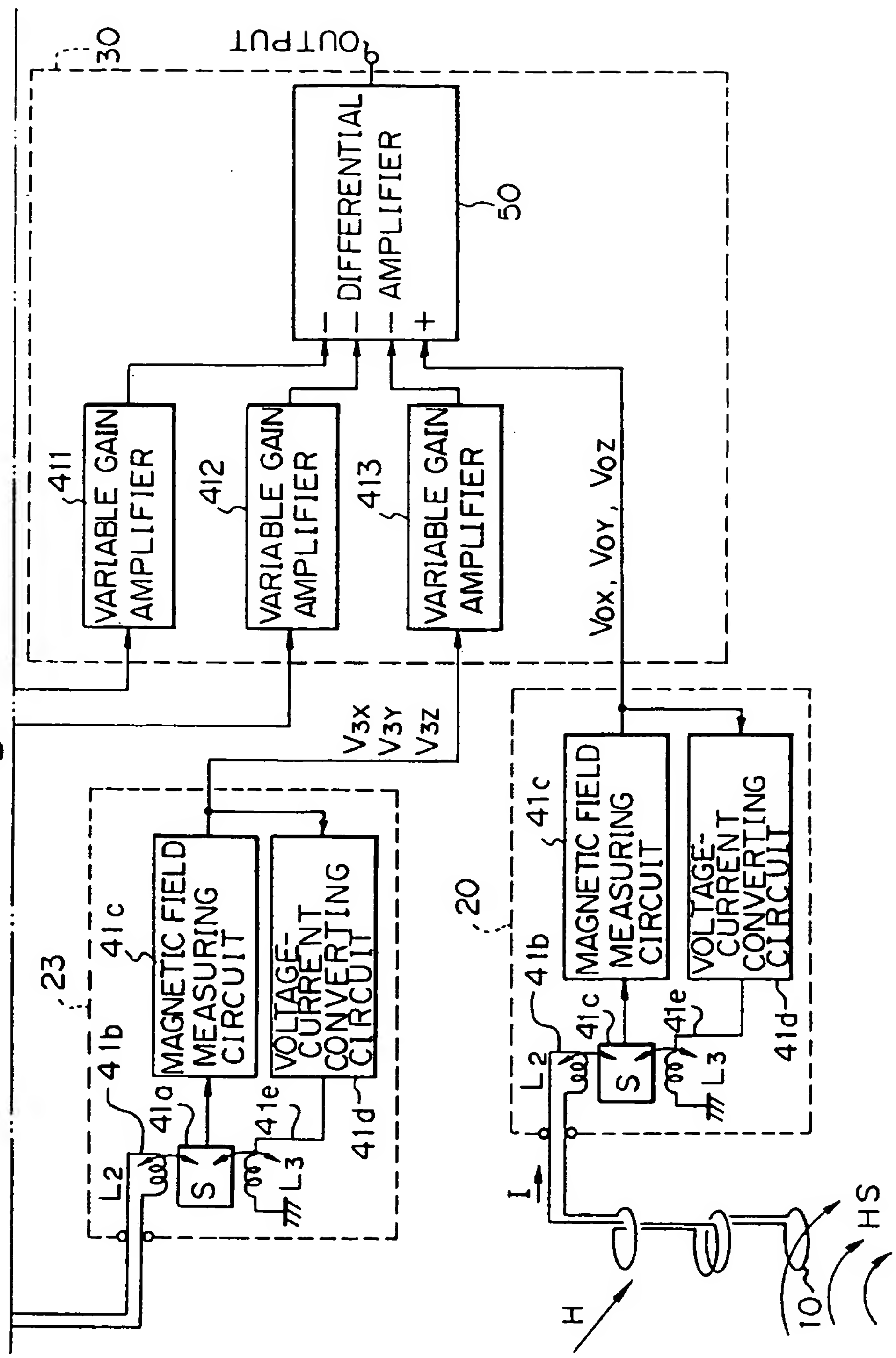

30
OUTPUT
DIFFERENTIAL AMPLIFIER
50
411
VARIABLE GAIN AMPLIFIER
412
VARIABLE GAIN AMPLIFIER
413
VARIABLE GAIN AMPLIFIER
Vox, Voy, Voz
V3x V3y V3z
23
41b
41c
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE-CURRENT CONVERTING CIRCUIT
41a
41e
41d
L2
L3
S
20
41b
41c
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE-CURRENT CONVERTING CIRCUIT
41c
41e
41d
L2
L3
S
I
H
HS
10

Fig. 6A

Fig. 6B

Fig. 6C

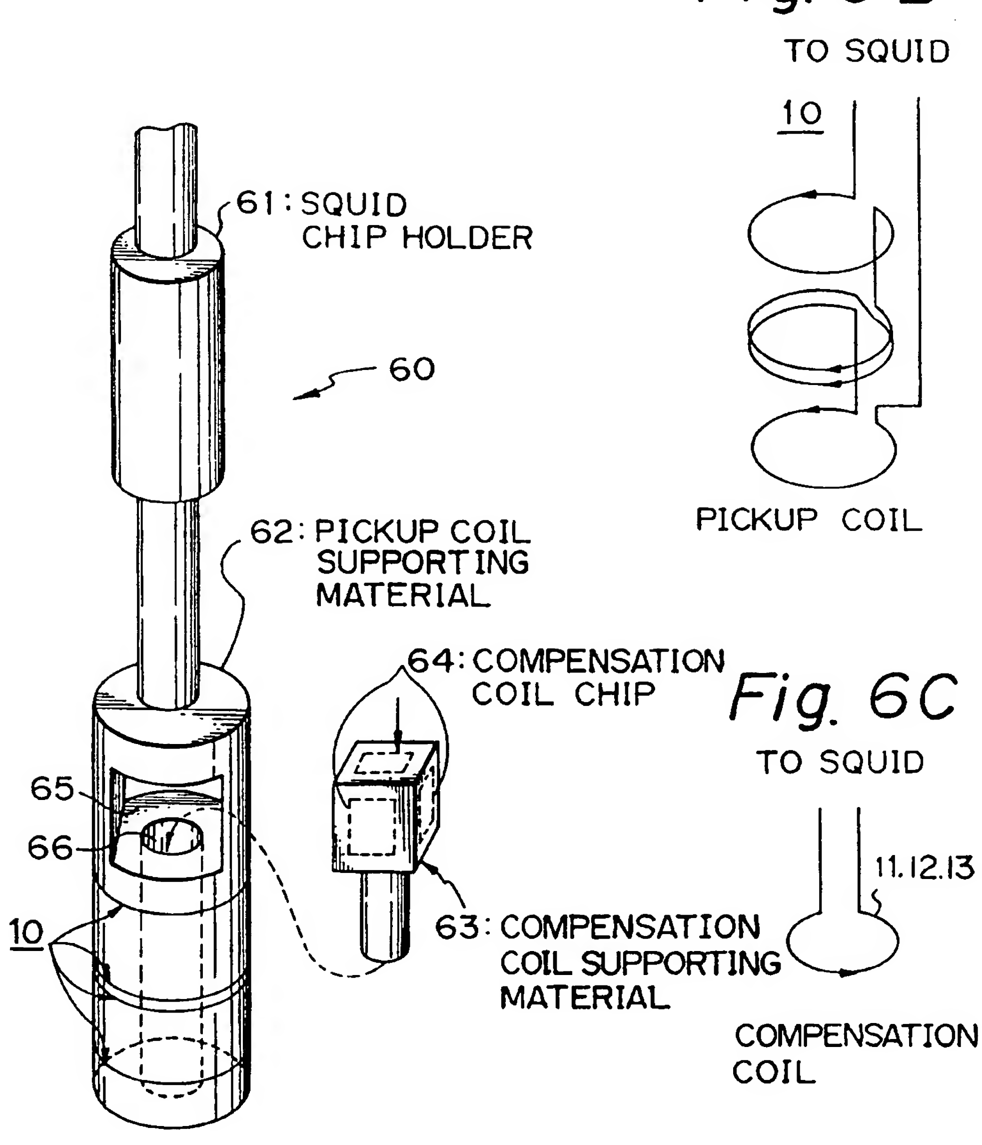


Fig. 7

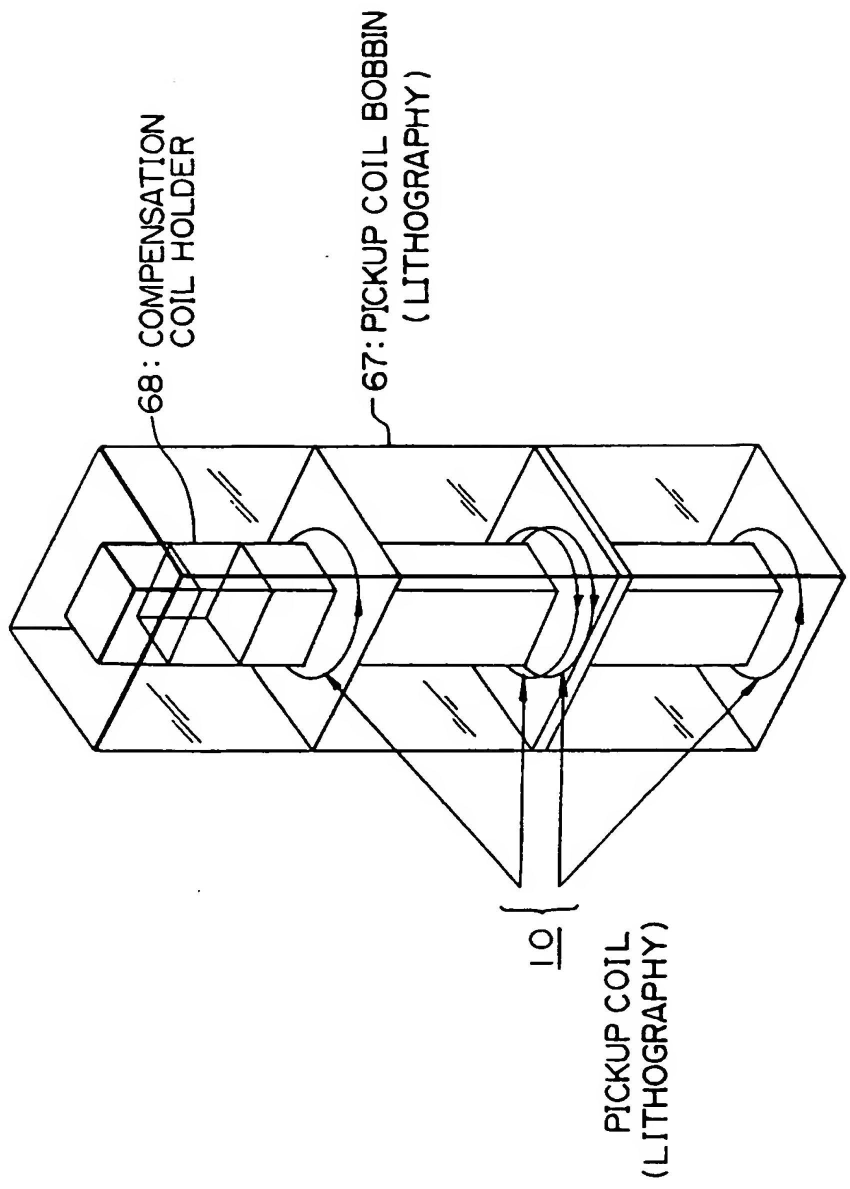

68: COMPENSATION
COIL HOLDER
67: PICKUP COIL BOBBIN
(LITHOGRAPHY)
10
PICKUP COIL
(LITHOGRAPHY)

Fig. 8

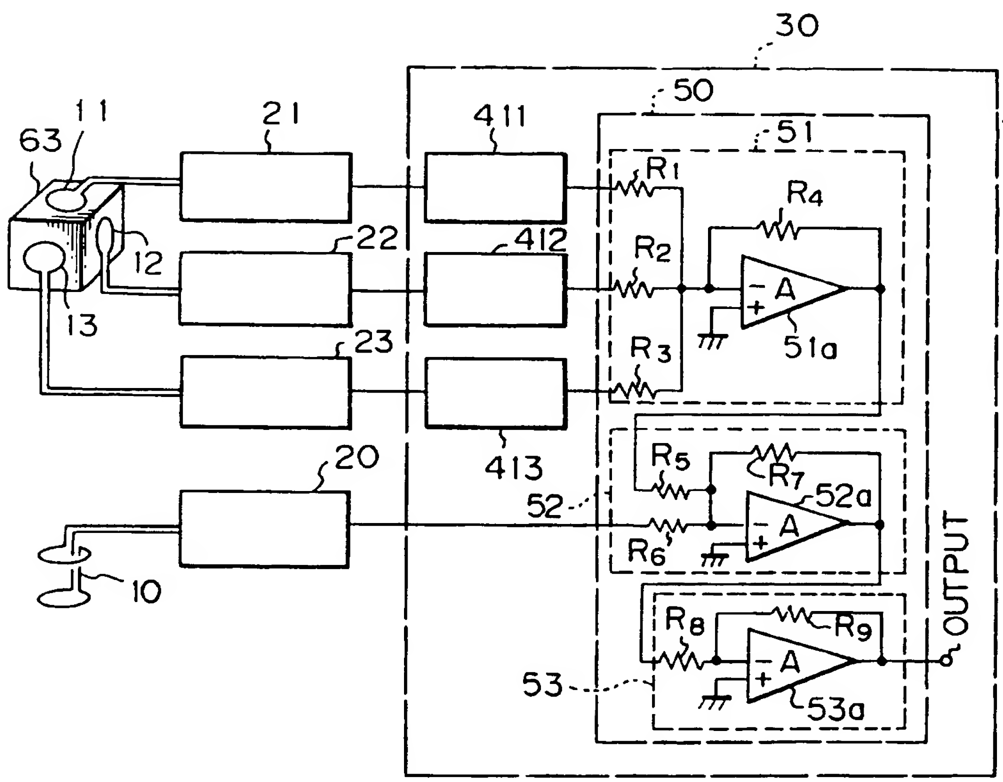

30
50
51
11
63
21
411
R1
R4
22
412
R2
12
A
13
51a
23
R3
20
413
R5
R7
52a
52
A
R6
OUTPUT
10
R8
R9
A
53
53a

Fig. 9

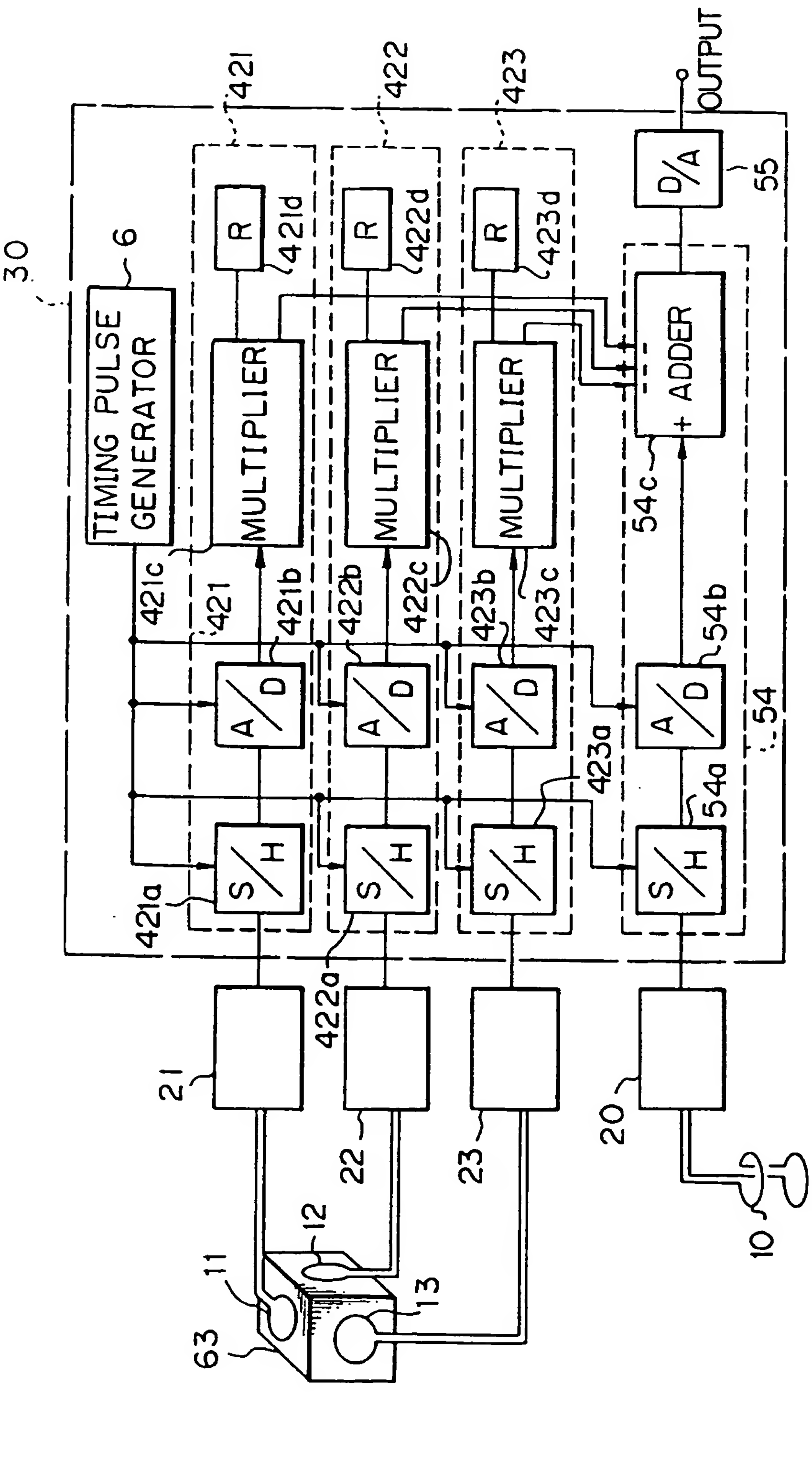

30
6
TIMING PULSE GENERATOR
421
422
423
MULTIPLIER
MULTIPLIER
MULTIPLIER
R
R
R
421d
422d
423d
421a
421b
421c
422a
422b
422c
423a
423b
423c
S/H
S/H
S/H
S/H
A/D
A/D
A/D
A/D
54
54a
54b
54c
ADDER
D/A
55
OUTPUT
21
22
23
20
10
11
12
13
63

Fig. 10

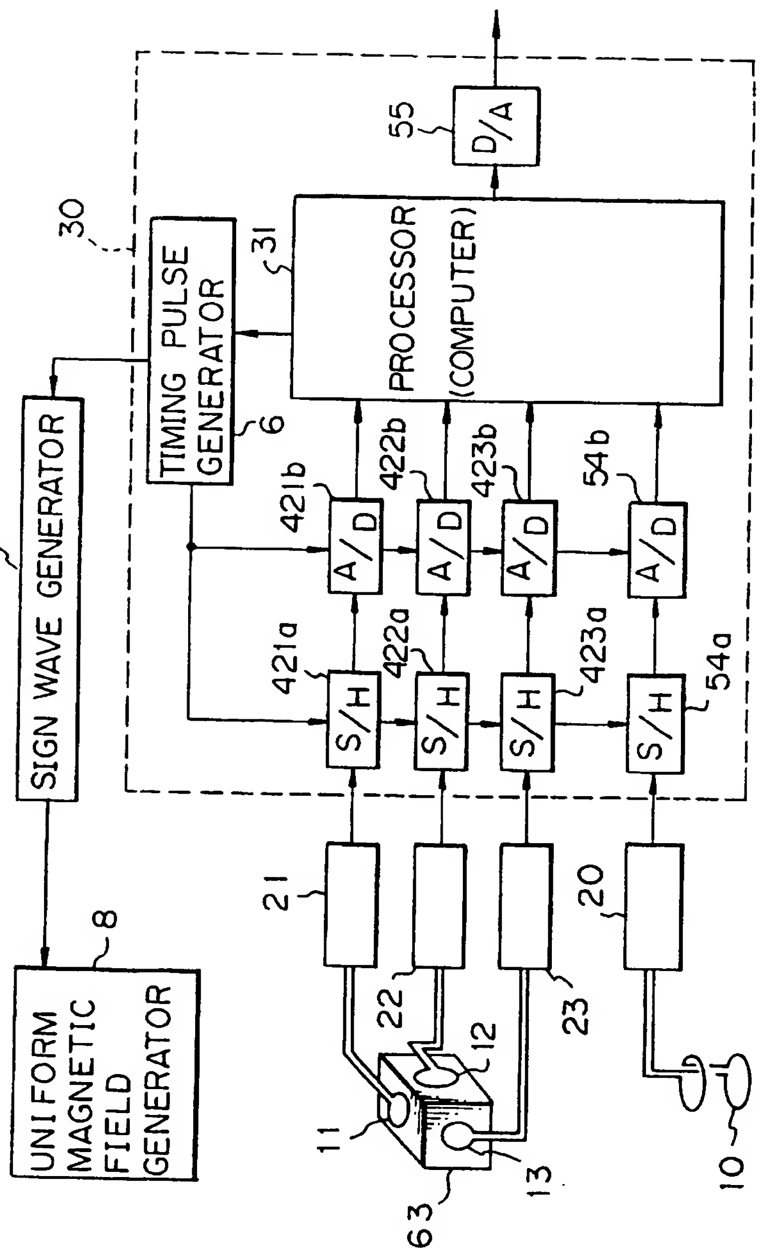

SIGN WAVE GENERATOR
7
UNI FORM MAGNETIC FIELD GENERATOR
8
TIMING PULSE GENERATOR
6
30
PROCESSOR (COMPUTER)
31
D/A
55
S/H
A/D
421a
421b
422a
422b
423a
423b
54a
54b
21
22
23
20
11
12
13
10
63

Fig. 11

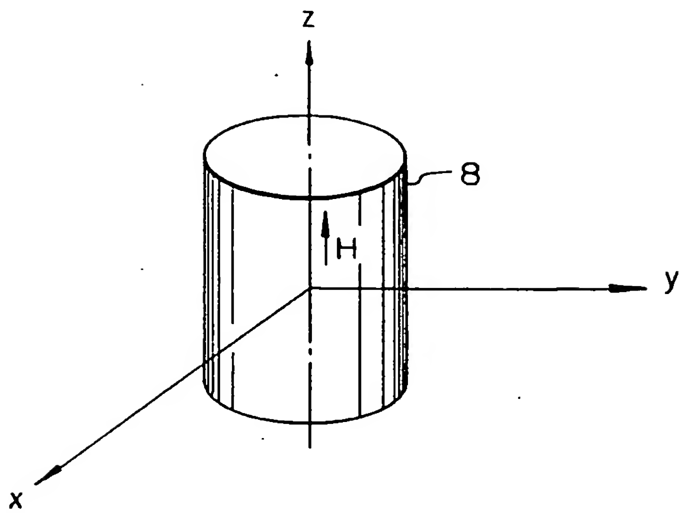

z
8
H
y
x

Fig. 15

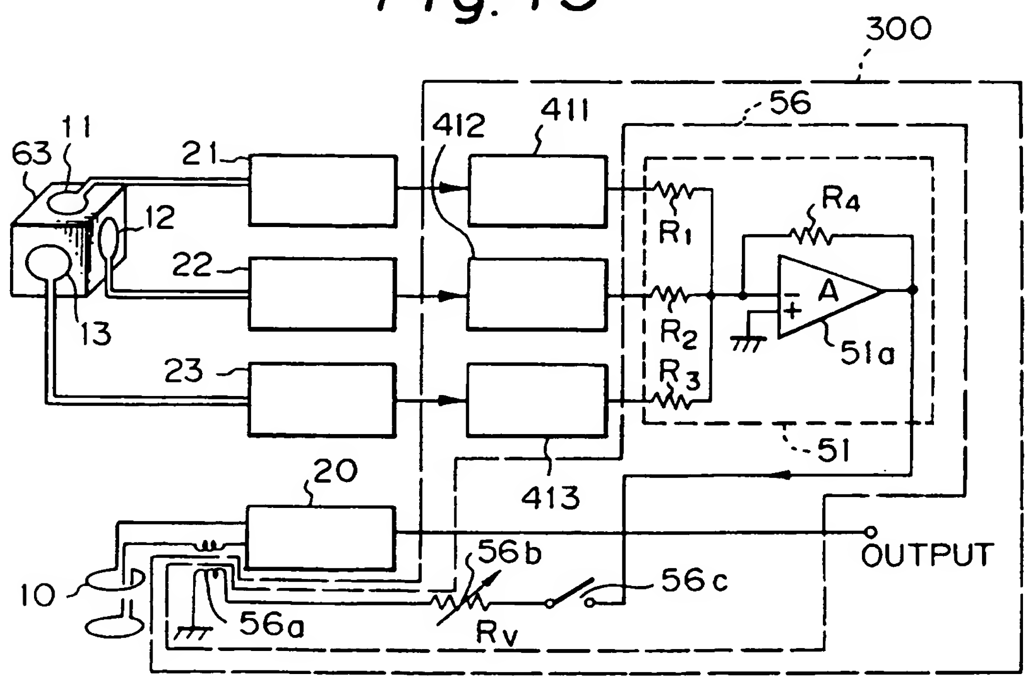

300
56
411
412
63
11
21
12
R4
R1
22
A
13
R2
51a
23
R3
51
20
413
56b
OUTPUT
56c
10
56a
Rv

Fig. 12

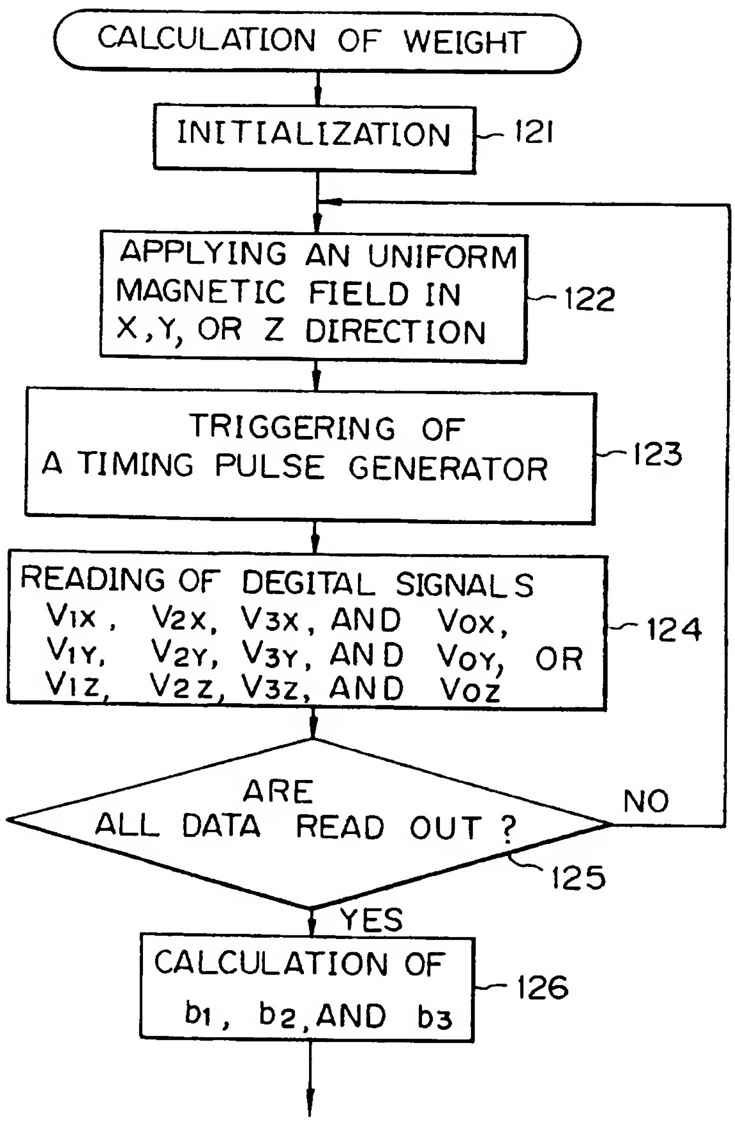
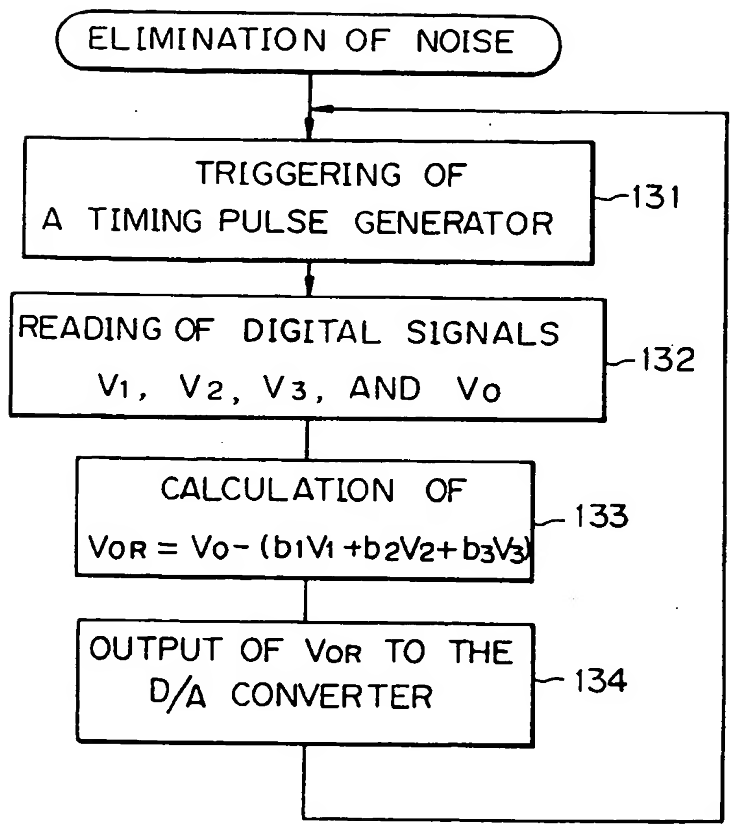
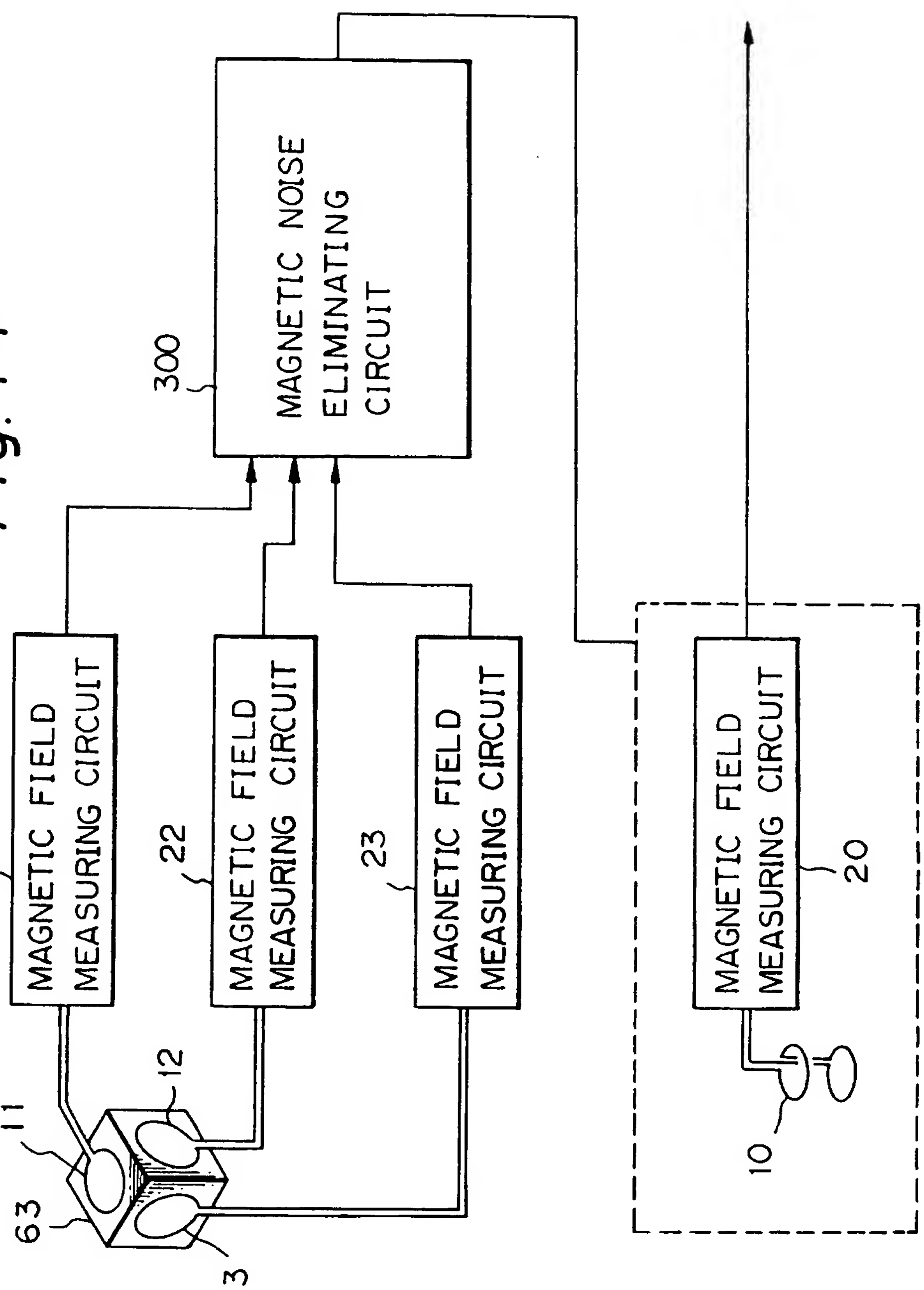

CALCULATION OF WEIGHT
INITIALIZATION
121
APPLYING AN UNIFORM MAGNETIC FIELD IN X,Y, OR Z DIRECTION
122
TRIGGERING OF A TIMING PULSE GENERATOR
123
READING OF DEGITAL SIGNALS V1X, V2X, V3X, AND V0X, V1Y, V2Y, V3Y, AND V0Y, OR V1Z, V2Z, V3Z, AND V0Z
124
ARE ALL DATA READ OUT ?
NO
125
YES
CALCULATION OF b1, b2, AND b3
126

Fig. 13


ELIMINATION OF NOISE
TRIGGERING OF A TIMING PULSE GENERATOR
131
READING OF DIGITAL SIGNALS V1, V2, V3, AND Vo
132
CALCULATION OF VoR = Vo - (b1V1 + b2V2 + b3V3)
133
OUTPUT OF VoR TO THE D/A CONVERTER
134



300
MAGNETIC NOISE ELIMINATING CIRCUIT
21
MAGNETIC FIELD MEASURING CIRCUIT
22
MAGNETIC FIELD MEASURING CIRCUIT
23
MAGNETIC FIELD MEASURING CIRCUIT
20
MAGNETIC FIELD MEASURING CIRCUIT
63
11
12
13
10

Fig. 14

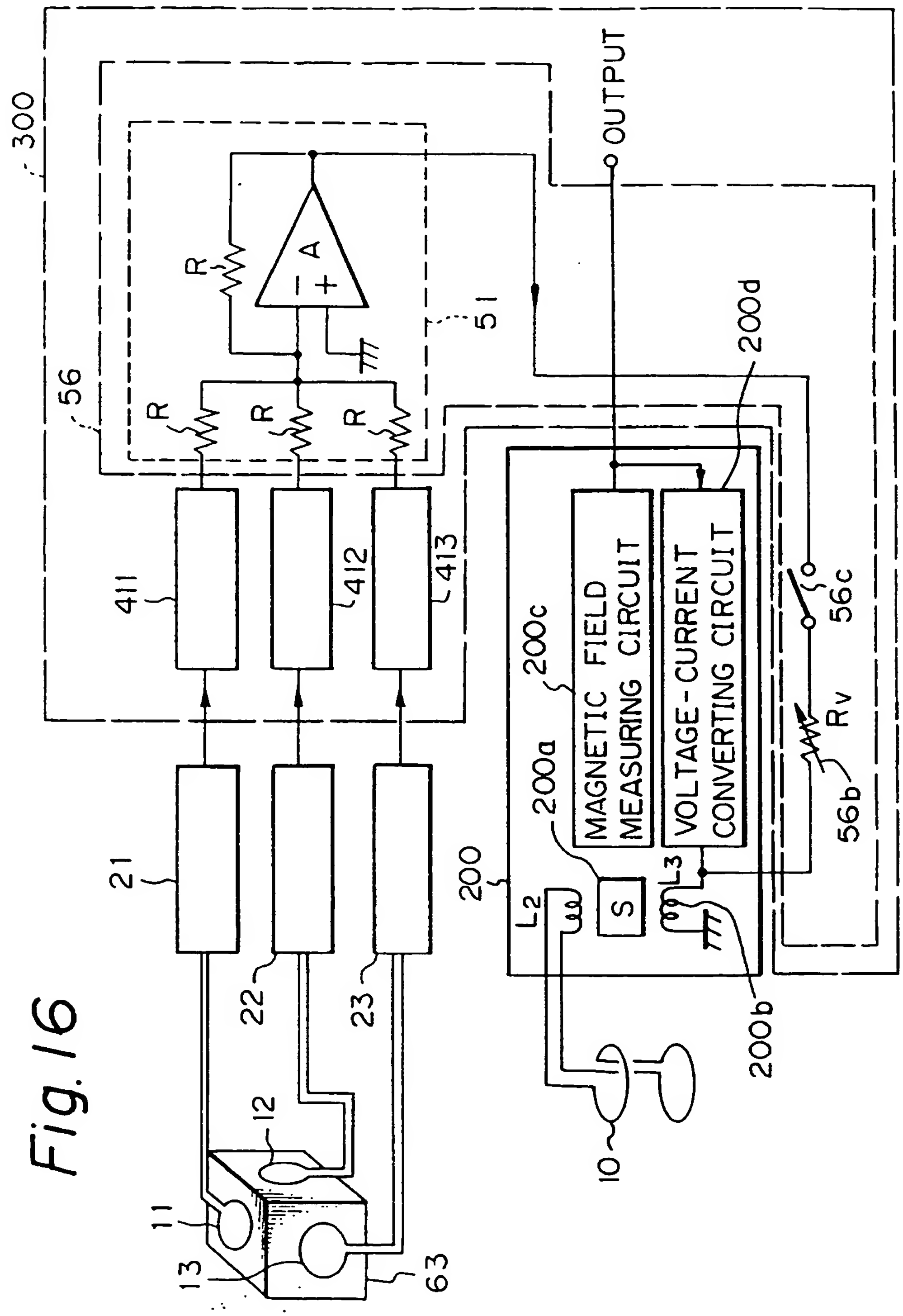

300
56
51
R
R
R
R
A
OUTPUT
200d
411
412
413
200c
MAGNETIC FIELD MEASURING CIRCUIT
VOLTAGE - CURRENT CONVERTING CIRCUIT
56c
Rv
56b
200a
S
L_3
L_2
200
200b
21
22
23
11
12
13
63
10

Fig. 16

Fig. 17

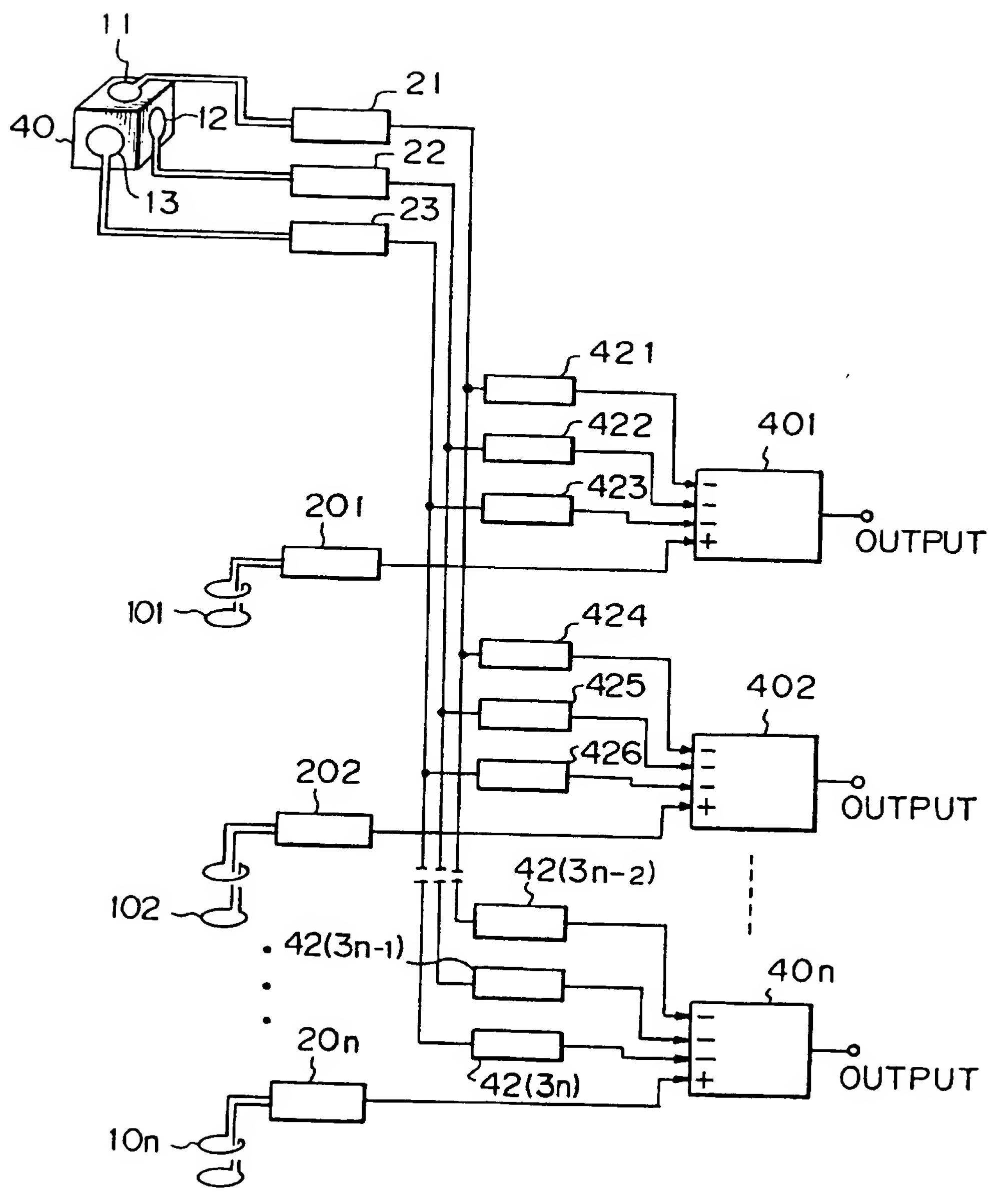

11
40
12
13
21
22
23
421
422
423
401
OUTPUT
201
101
424
425
426
402
OUTPUT
202
102
42(3n-2)
42(3n-1)
40n
20n
42(3n)
OUTPUT
10n

Fig. 18

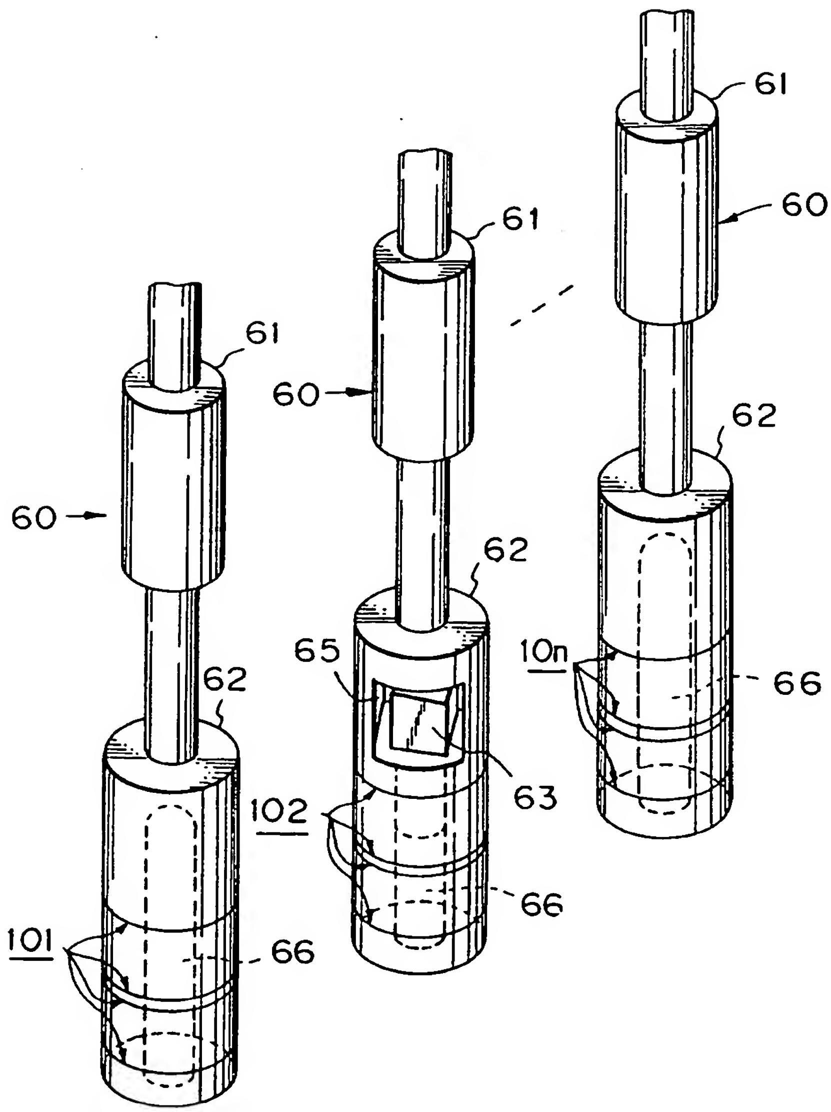
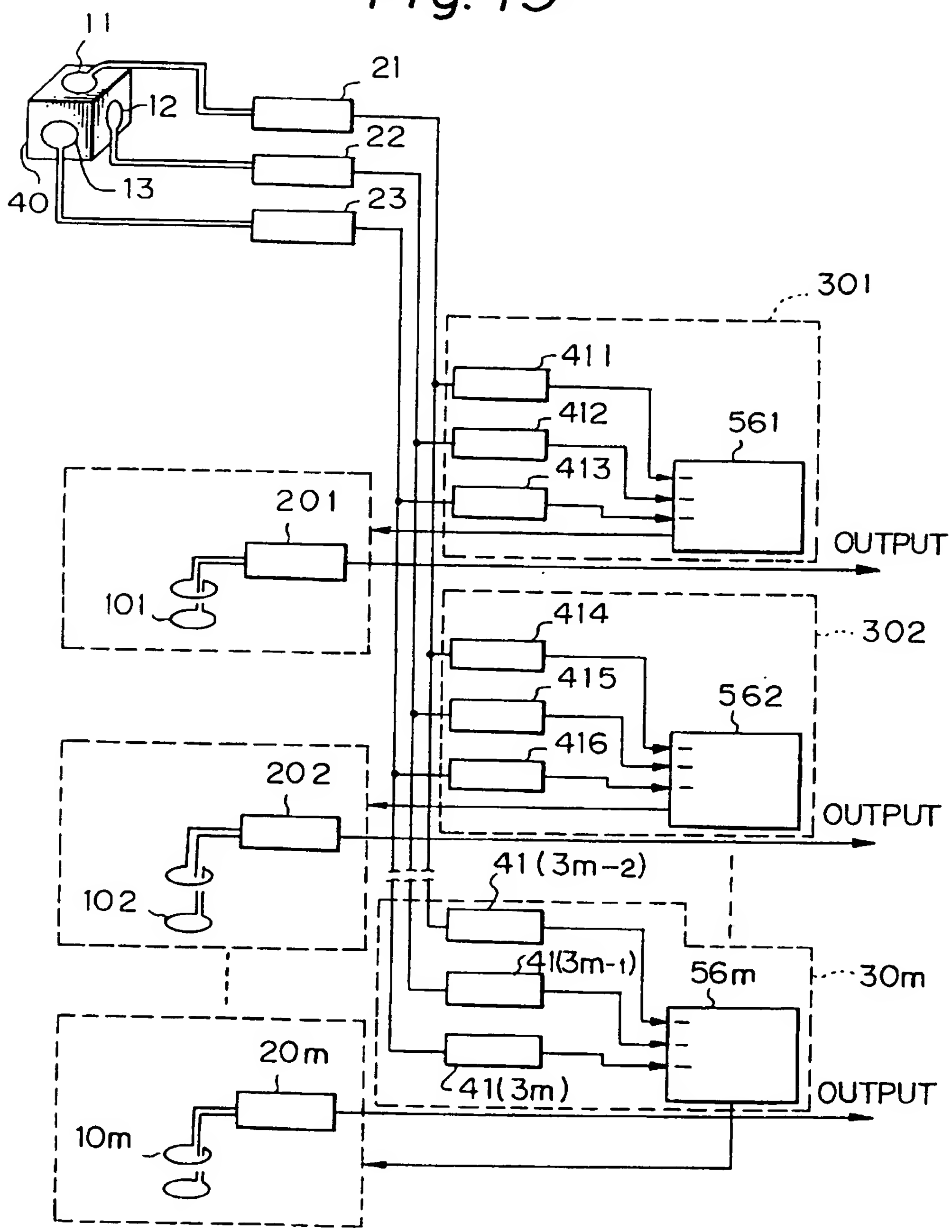


Fig. 19


11
12
13
40
21
22
23
301
411
412
413
561
OUTPUT
201
101
414
415
416
302
562
OUTPUT
202
102
41(3m−2)
41(3m-1)
56m
30m
41(3m)
OUTPUT
20m
10m